Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation:

Technical Support Document

United States Environmental Protection Agency

Proposed Determination on the Appropriateness of the Model Year 2022-2025 Light-Duty Vehicle Greenhouse Gas Emissions Standards under the Midterm Evaluation:

Technical Support Documnet

Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

EPA United States Environmental Protection Agency

EPA-420-R-16-021
November 2016

TABLE OF CONTENTS

This Page Intentionally Left Blank

List of Acronyms

2MHEV	2-Mode Hybrid
ABS	Anti-lock Braking System
ABT	Averaging, Banking, and Trading
AC	Alternating Current
A/C	Air Conditioning
ACEEE	American Council for an Energy-Efficient Economy
AEO	Annual Energy Outlook
AER	All-Electric Range
AFDC	Alternative Fuels Data Center
AGM	Absorbent Glass Mat
AHSS	Advanced High Strength Steel
ALPHA	Advanced Light-Duty Powertrain and Hybrid Analysis Tool
AMT	Automated Manual Transmission
ANL	Argonne National Laboratory
ARB	California Air Resources Board
ASI	Area Specific Impedance
ASL	Aggressive Shift Logic
ASM	Annual Survey of Manufacturers
AT	Automatic Transmissions
Avg	Average
AWD	All Wheel Drive
BenMAP	Benefits Mapping and Analysis Program
BEV	Battery Electric Vehicle
BISG	Belt Integrated Starter Generator
BIW	Body-In-White
BLS	Bureau of Labor Statistics
BMEP	Brake Mean Effective Pressure
BOM	Bill of Materials
BSFC	Brake Specific Fuel Consumption
BTE	Brake-Thermal Efficiency
BTU	British Thermal Unit
CAA	Clean Air Act
CAD	Computer Aided Designs
CAD/CAE	Computer Aided Design and Engineering
CAE	Computer Aided Engineering
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CAVs	Connected and Automated (or autonomous) Vehicles
CBD	Center for Biological Diversity
CBI	Confidential Business Information
CCP	Coupled Cam Phasing

CDPF	Catalyzed Diesel Particulate Filter
CEC	California Energy Commission
CES	Consumer Expenditure Survey
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
CH_4	Methane
CISG	Crank Integrated Starter Generator
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq	CO2 Equivalent
COP	Coefficient of Performance
CSM	Conceptual Site Model
CSV	Comma-separated Values
CUV	Crossover Utility Vehicles
CVT	Continuously Variable Transmission
CY	Calendar Year
DC	Direct Current
DCFC	Direct Carbon Fuel Cell
DCP	Dual Cam Phasing
DCT	Dual Clutch Transmission
DEAC	Cylinder Deactivation
DFMA™	Design for Manufacturing and Assembly
DGS	California Department of General Services
DICE	Dynamic Integrated Climate and Economy
DMC	Direct Manufacturing Costs
DoE	Department of Energy
DOE	Design of Experiments
DOHC	Dual Overhead Camshaft Engines
DOT	Department of Transportation
DRI	Dynamic Research, Inc.
DRLs	Daytime Running Lamps
DVVL	Discrete Variable Valve Lift
EGR	Exhaust Gas Recirculation
EHPS	Electrohydraulic Power Steering
EIA	Energy Information Administration (part of the U.S. Department of Energy)
EISA	Energy Independence and Security Act
EIVC	Early Intake Valve Closing
EPA	Environmental Protection Agency
EPCA	Energy Policy and Conservation Act
EPRI	Electric Power Research Institute
EPS	Electric Power Steering

EPS	Energy Power Systems
EREV	Extended Range Electric Vehicle
ERM	Employment Requirements Matrix
ESC	Electronic Stability Control
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FARS	Fatality Analysis Reporting System
FCEV	Fuel Cell Electric Vehicle
FCPM	Fuel Cost Per Mile
FCEV	Fuel Cell Electric Vehicle
FE	Finite Element
FEV1	Functional Expiratory Volume
FHWA	Federal Highway Administration
FMEP	Friction Mean Effective Pressure
FMVSS	Federal Motor Vehicle Safety Standards
FR	Federal Register
FRIA	Final Regulatory Impact Analysis
FRM	Federal Rulemaking
FRM	Federal Reference Method
FTP	Federal Test Procedure
gal/mi	Gallon/Mile
GCWR	Gross Combined Weight Rating
GDI	Gasoline Direct Injection
GDP	Gross Domestic Product
GEM	Greenhouse gas Emissions Model
GHG	Greenhouse Gases
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
GWU	George Washington University
HD	Heavy-Duty
HEV	Hybrid Electric Vehicle
HFC	Hydrofluorocarbon
HFET	Highway Fuel Economy Dynamometer Procedure
HIL	Hardware-In-Loop
hp	Horsepower
hrs	Hours
HP/WT	Horsepower Divided by Weight
HVAC	Heating, Ventilating, And Air Conditioning
hz	Hertz
IACC	Improved Accessories
IAM	Integrated Assessment Models

IATC	Improved Automatic Transmission Control
IC	Indirect Cost
ICCT	International Council on Clean Transport
ICF	ICF International
ICM	Indirect Cost Multiplier
ICMs	Indirect Cost Markups
IHX	Internal Heat Exchanger
IMA	Improved Mobile Assist
IMAC	Improved Mobile Air Conditioning
INL	Idaho National Laboratory
IOU	Investor Owned Utilities
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Planning Model
ITC	Institute of Transportation Studies
IWG	Interagency Working Group
k	Thousand
kg	Kilogram
kW	Kilowatt
kWh	kilowatt-hour
L	Liter
lb	Pound
LBNL	Lawrence Berkeley National Laboratory
LD	Light-Duty
LEV	Low-Emission Vehicle
LHD	Light Heavy-Duty
LDV	Light Duty Vehicle
LNT	Lean NOx Trap
LRR	Lower Rolling Resistance
LT	Light Trucks
LWT	Lightweighted Pickup Truck
MAD	Minimum Absolute Deviation
MBPD	Million Barrels Per Day
MD	Medium-Duty
MDPV	Medium-Duty Passenger Vehicles
MEMA	Motor Equipment Manufacturers Association
Mg	Megagrams
mg	Milligram
MHEV	Mild Hybrid
mi	mile
min	minimum
min	Minute
MM	Million
MMLV	Multi-Material Lightweight Vehicle

MMT	Million Metric Tons
MOVES	Motor Vehicle Emissions Simulator
mpg	Miles per Gallon
mph	Miles per Hour
MPV	Multi-Purpose Vehicle
MSRP	Manufacturer's Suggested Retail Price
MTE	Mid Term Evaluation
MuD	Multi-Unit Development
MY	Model Year
N_2O	Nitrous Oxide
NA	Not Applicable
NAAQS	National Ambient Air Quality Standards
NADA	National Automobile Dealers Association
NAS	National Academy of Sciences
NCA	National Climate Assessment
NCAP	New Car Assessment Program
NEMS	National Energy Modeling System
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NF_3	Nitrogen Trifluoride
NGO	Non-Governmental Organization
NHTSA	National Highway Traffic Safety Administration
NiMH	Nickel Metal-Hydride
NF_3	Nitrogen Trifluoride
NOX	Nitrogen Oxides
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
NPRM	Notice of Proposed Rulemaking
NRC	National Research Council
NRC-CAN	National Research Council of Canada
NREL	National Renewable Energy Laboratory
NVH	Noise Vibration and Harshness
NVPP	National Vehicle Population Profiles
OAR	EPA's Office of Air and Radiation
OEM	Original Equipment Manufacturer
OECD	Organization for Economic Cooperation and Development
OHV	Overhead Valve
OLS	Ordinary Least Squares
OMB	EPA's Office of Management and Budget
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
OTAQ	EPA's Office of Transportation and Air Quality
PAGE	Policy Analysis of the Greenhouse Effect
PC	Passenger Car

P/E	Power-to-Energy
PEF	Peak Expiratory Flow
PEV	Plug-in Electric Vehicle
PFCs	Perfluorocarbons
PFI	Port-fuel-injection
PGM	Platinum Group Metal
PHEV	Plug-in Hybrid Electric Vehicle
PLM	Planar Layered Matrix
PM	Particulate Matter
$PM_{2.5}$	Fine Particulate Matter (diameter of 2.5 µm or less)
PMSMs	Permanent-Magnet Synchronous Motors
PSHEV	Power-split Hybrid
PSI	Pounds per Square Inch
PWM	Pulse-width Modulated
R&D	Research and Development
RFS2	Renewable Fuel Standard 2
RIA	Regulatory Impact Analysis
RPE	Retail Price Equivalent
RPM	Revolutions per Minute
RSM	Response Surface Models
RTI	RTI International (formerly Research Triangle Institute)
SA	Strategic Analysis, Inc.
SAB	Science Advisory Board
SAB-EEAC	Science Advisory Board Environmental Economics Advisory Committee
SAE	Society of Automotive Engineers
$SC0_3$	Soak Control third iteration
SCC	Social Cost of Carbon
SCR	Selective Catalyst Reduction
SF_6	Sulfur Hexafluoride
SGDI	Stoichiometric Gasoline Direct Injection
SHEV	Strong Hybrid Electric Vehicles
SI	Spark-Ignition
SIDI	Spark Ignition Direct Injection
SIL	Software-In-Loop
SMDI	Steel Market Development Institutes
SNAP	Significant New Alternatives Policy
SNPRM	Supplemental Notice of Proposed Rulemaking
SO_2	Sulfur Dioxide
SO_x	Sulfur Oxides
SOC	State of Charge
SOHC	Single Overhead Cam

SOL	Small Overlap
SPR	Strategic Petroleum Reserve
Std	Standard
SUV	Sport Utility Vehicle
TAR	Technical Assessment Report
TC	Total Costs
TCIP	Tire Consumer Information Program
TDC	Top Dead Center
Tds	Direct Solar Transmittance
TFECIP	Tire Fuel Efficiency Consumer Information Program
TPE	Total Primary Energy
TRBDS	Turbocharging and Downsizing
TSD	Technical Support Document
UMTRI	University of Michigan Transportation Research Institute
UTQGS	Uniform Tire Quality Grading Standards
V2V	Vehicle-To-Vehicle
VGI	Vehicle Grid Integration
VIF	Variance Inflation Factor
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound
VSL	Vehicle Speed Limiter
VVL	Variable Valve Lift
VVT	Variable Valve Timing
WT/FP	Weight Divided By Footprint

Executive Summary

The rulemaking establishing the National Program for Federal greenhouse gas (GHG) emissions and corporate average fuel economy (CAFE) standards for model year (MY) 2017-2025 light-duty vehicles included a regulatory requirement for the Environmental Protection Agency (EPA) to conduct a Midterm Evaluation (MTE) of the greenhouse gas (GHG) standards established for MYs 2022-2025. Through the MTE, EPA must determine no later than April 1, 2018 whether the MY2022-2025 GHG standards, established in 2012, are still appropriate under section 202 (a) (1) of the Clean Air Act ("Act"), in light of the record then before the Administrator, given the latest available data and information. The Administrator is making a Proposed Determination that the MY2022-2025 standards adopted in the 2012 final rule establishing the MY2017-2025 standards remain appropriate under section 201 (a) (1) of the Act. This Technical Support Document (TSD) provides additional detailed analyses supporting this Proposed Determination.

The Proposed Determination follows the July 2016 release of a Draft Technical Assessment Report (TAR), issued jointly by EPA, National Highway Traffic Safety Administration (NHTSA), and the California Air Resources Board (CARB). EPA requested comment on the analysis supporting the Draft TAR and has fully considered those public comments as well as other new information, and has updated its analyses where appropriate as part of this Proposed Determination. This TSD describes in more detail our assessment of public comment on the Draft TAR and updates to our technology costs, technology effectiveness, consumer impacts, and other elements of our analysis.

A summary of each chapter of the TSD follows:

Chapter 1: Baseline and Reference Vehicle Fleets. This chapter describes EPA's methodologies for developing a baseline fleet of vehicles and future fleet projections out to MY2025. The Proposed Determination analysis uses a baseline fleet based on the MY2015 fleet, the latest year available for which there are final GHG compliance data. EPA used data from Energy Information Administration's Annual Energy Outlook 2016 (AEO 2016) as the basis for total vehicle sales projections to 2025, as well as for the car and truck volume mix.

Chapter 2: Technology Costs, Effectiveness, and Lead Time Assessment. This chapter is an in-depth assessment of the state of vehicle technologies to reduce GHG emissions and improve fuel economy, as well as EPA's assessment of expected future technology developments through MY2025. The technologies evaluated include all those considered for the 2012 final rule and the Draft TAR, as well as new technologies that have emerged. Every technology has been reconsidered with respect to its cost, effectiveness, application, and lead time considerations, with emphasis on assessing the latest introductions of technologies to determine if and how they have changed.

Chapter 3: Economic and Other Key Inputs Used in EPA's Analyses. This chapter describes many of the economic and other inputs used in the Proposed Determination analyses. This chapter discusses the methodologies used to assess inputs such as the real-world fuel economy/GHG emissions gap, vehicle miles traveled (VMT), vehicle survival rates, the VMT rebound effect, energy security, the social cost of carbon and other GHGs, health benefits, consumer cost of vehicle ownership, and others.

Chapter 4: Consumer Issues. This chapter reviews issues surrounding consumer acceptance of the vehicle technologies expected to be used to meet the MY2022-2025 standards. Since the GHG standards have been in effect since MY2012, EPA focuses on the evidence to date related to consumer acceptance of vehicles subject to these standards. This chapter also discusses potential impacts of the standards on vehicle sales and affordability, which are closely interconnected with the effects of macroeconomic and other market forces.

Chapter 5: EPA's OMEGA Model. This chapter describes EPA's computerized program called the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA), the model used to efficiently apply technologies to the wide range of vehicles produced by various manufacturers.

Table of Contents

Table of Figures

Table of Tables

Chapter 1: Baseline and Reference Vehicle Fleets

1.1 Baseline and Reference Vehicle Fleets

The passenger cars and light trucks sold currently in the United States, and those that are anticipated to be sold in the model years (MYs) 2021-2025 time frame, are highly varied and satisfy a wide range of consumer needs. From two-seater miniature cars to 11-seater passenger vans to large extended cab pickup trucks, American consumers have a great number of vehicle options to accommodate their needs and preferences. The recent decline in oil prices and the improved state of the economy have demonstrated that consumer demand and choice of vehicles within this wide range can be sensitive to these factors. Although it is impossible to precisely predict the future, a starting point of any analysis must be to characterize and quantify a future fleet in order to assess the impacts of the 2022-2025 GHG standards that would affect that future fleet. As in the FRM and the Draft TAR, EPA has examined various publicly-available sources (some requiring purchase), and then used inputs from those sources in a series of models to project the composition of baseline and reference fleets for the purposes of this analysis. This chapter describes this process, and the characteristics of the baseline and reference fleets.

EPA has made every effort to make this analysis transparent and duplicable. Because both the input and output sheets from our modeling are public,[1] stakeholders can verify and check EPA's modeling results, and use the results to perform their own analyses.

1.1.1 <u>Why does EPA Establish Baseline and Reference Vehicle Fleets?</u>

In order to calculate the impacts of the final 2022-2025 GHG standards, it is necessary to estimate the composition of the future vehicle fleet absent the 2022-2025 standards. EPA has developed a baseline/reference fleet in two parts. The first step was to develop a "baseline" fleet. The baseline fleet represents data from a single model year of actual vehicle sales. EPA creates a baseline fleet in order to track the volumes and types of CO_2-reducing technologies that are already present in the existing vehicle fleet. Creating a baseline fleet accounts for technologies already deployed in the fleet, and thus not only is a necessary step in assessing what additional technologies might be added and the costs and benefits of adding those technologies, but also avoids double-counting of those costs and benefits. Specifically, an accurate assessment of the baseline fleet prevents the OMEGA model from adding technologies to vehicles that already have these technologies, which would result in such double-counting.

The second step was to project the baseline fleet sales into MYs 2022-2025. This is called the "reference" fleet volumes, and it represents the fleet volumes (but, until later steps, not additional levels of technology) that EPA believes would exist in MYs 2022-2025 absent the application of the 2022-2025 GHG standards.

After determining the reference fleet volumes, the third step is to account for technologies (and corresponding increases in cost and reductions in CO_2 emissions) that could be added to the baseline technology vehicles in the future, taking into account previously-promulgated standards, and assuming MY2021 standards apply at the same levels through MY2025. This step uses the OMEGA model to add technology to each vehicle in the baseline market forecast such that each manufacturer's car and truck average CO_2 levels reflect that manufacturer's projected MY2021 standards. The model's output, the "reference case," is the light-duty fleet estimated to exist in

MYs 2022-2025 without new GHG standards (that is, without any standards beyond the MY2021 standards). All of EPA's estimates of emission reduction improvements, costs, and societal impacts for purposes of this Proposed Determination are developed in relation to the reference case.

This chapter describes the first two steps of the development of the baseline and reference fleets volumes. The third step is technology addition which is developed as the outputs of the OMEGA model (see Chapter 5 for an explanation of how the models apply technologies to vehicles in order to evaluate potential paths to compliance).

1.1.2 Key Comments on EPA's MY2014 Baseline Fleet Used in the Draft TAR

For the Draft TAR, EPA chose to create a baseline fleet based on MY2014 data because, at the time, it was the most recent year for which a complete set of certification data was available. See Draft TAR at p. 4-2 and 4-9. In general, several commenters (for example, Union of Concerned Scientists and Environmental Defense Fund) supported EPA's use of MY2014 data since it was the latest year of final compliance data. The Alliance of Automobile Manufacturers (AAM) sent mixed messages in their comments. AAM noted that MY2015, used by NHTSA in its CAFE analysis, was more recent and urged that EPA use the latest data available. AAM went on to say that we should use the data that was available 90 days after the end of production, which was MY2014 data. However, in order to create a baseline fleet that meets the AAM suggestion, EPA would need to create the fleet based on manufacturer provided mid-year reports. The mid-year reports do not constitute data -- these reports are estimates of what the manufacturer's year end production and GHG performance are projected to be. See Draft TAR at p. 4-9. The estimated GHG values along with the estimated volume values thus may not give an accurate view of the fleet.

Global Automakers commented that EPA included vehicles in its modeling that were no longer in production. However, manufacturers will often eliminate a model in a vehicle class and later have a new model enter the same vehicle class. Thus, the fact that a model is discontinued does not mean that the class of vehicle will no longer be represented in the future fleet. EPA picks a model year of vehicles and then projects them forward based on their vehicle class. There is an initial assumption that all vehicles in that model year are needed to represent the needs of the public. EPA then used the IHS-Polk forecast to determine if a class of vehicle might be discontinued. Put another way, for projecting the future vehicle fleet, EPA changes the proportions of vehicles in a vehicle class based on IHS-Polk's forecast to represent the public's future needs, but does not automatically eliminate a class of vehicle because a particular model is discontinued. The only way a vehicle is eliminated is if a manufacturer no longer participates in a vehicle class. In short, eliminating a model would eliminate a choice that is assumed to be needed by the public unless its class has been eliminated by the IHS-Polk forecast.

Our concerns regarding use of a mid-year report is now obviated, however, because final certification data from the EPA Verify Database for MY2015 is now available. Consistent with the approach in the Draft TAR of using the most recent final certification data for the baseline year, EPA is using these data for establishing the baseline fleet. See Draft TAR pp. 4-2 and 4-9; for a description of the Verify Database, see the following Chapter 1.1.3.

Commenters also urged EPA and NHTSA to use a common baseline for future analysis. Although this analysis is not a joint exercise, EPA has moved to MY2015 since final data is now available. As stated in the Draft TAR and reconfirmed above, EPA uses the most recent model year for which final sales data is available for its analysis.

AAM commented that EPA should consider using a multi-year average instead of a single year for the baseline. EPA believes that using a multi-year average would be problematic since technology on vehicles changes from year to year which would make accurately representing a multi-year averaged fleet extremely challenging.

AAM also voiced the belief that we had removed 800,000 vehicles from the AEO's projections. The tables we provided are in fact consistent with what EIA published for AEO2015. See Chapter 1.1.3.1.1 below. AAM also commented that we could have used our contractor's (IHS-Polk) projections of total vehicle sales. However, EIA is the standard government-wide reference, and for EPA to deviate from that source would put us out of step with the rest of the federal government. EPA believes that consistency on total volumes across agencies should be pursued where feasible, and believes that EIA's projections are the best available source for projections of total car and total light truck sales.

1.1.3 MY2015 Baseline Fleet used for this Proposed Determination

EPA has updated the basis for the baseline fleet used in the Proposed Determination analysis to reflect MY2015, the latest available model year for which there is final manufacturer GHG certification data. The MY2015 fleet GHG data is the most recent complete set of final U.S. vehicle data that includes actual manufacturer volumes and CO_2 values. The MY2015 volumes and CO_2 values come from the EPA Verify[A] database. The data contained in the Verify system is quite robust since it undergoes a complex number of quality checks that are performed first by the manufacturer, then by the Verify database software, and finally by EPA's certification staff. Figure 1.1 shows the quality steps that are completed before data is available for use in the Verify system. The finalized 2015 GHG certification data is thus the most accurate representation of vehicle and technology mix for MY2015.[B] As noted above, this baseline fleet is not identical to that established by NHTSA in the Draft TAR, since that fleet reflected mid-year manufacturer reports. See Draft TAR Chapter 13.1.1. EPA supplemented this data with valve train information from Wards Automotive Group,[C,D] and curb weights and power steering information from NHTSA's 2015 Volpe Baseline Fleet file created for the Draft TAR.

[A] The EPA Verify Database is the electronic system by which vehicle manufacturers provide their compliance data to EPA. There are several built-in quality assurance provisions.

[B] We note that this 2015 MY baseline fleet is not identical to that established by NHTSA in the Draft TAR, since that fleet reflected mid-year manufacturer reports rather than the final certified data used here. See Draft TAR Chapter 13.1.1.

[C] WardsAuto.com: Used as a source for engine specifications shown in Figure 1.2.

[D] Note that WardsAuto.com, where this information was obtained, is a fee-based service, but all information is public to subscribers.

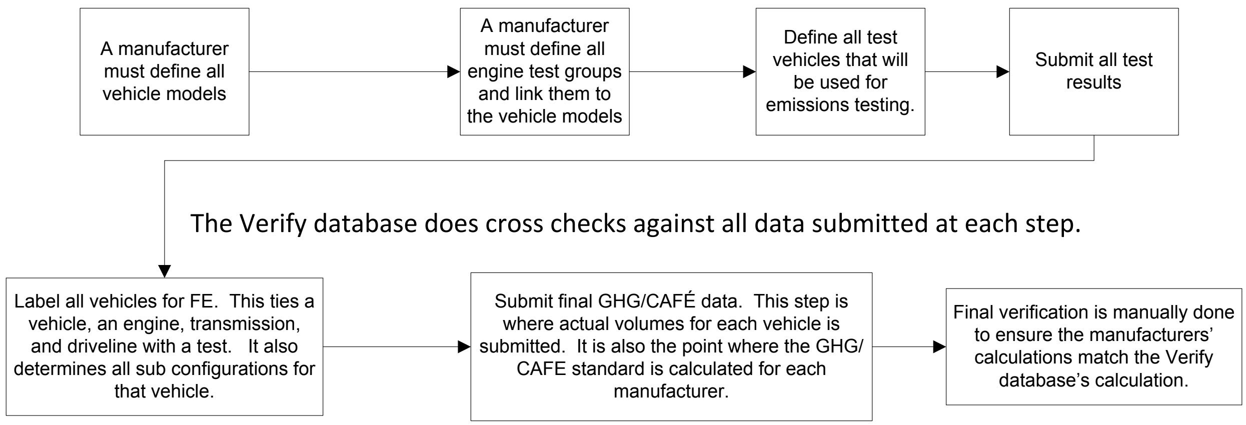


Figure 1.1 The Verify Process for the Data EPA's MY2015 Baseline Vehicle Fleet is Based

Similar to the 2008 baseline that EPA used in the 2017-2025 GHG FRM and the 2014 baseline fleet used for the Draft TAR, most of the information about the vehicles that make up the 2015 fleet was gathered from EPA's emission certification and fuel economy database, most of which is publicly available. (Note that a 2010 baseline was created for the 2017-2025 GHG FRM, but it was only used for a sensitivity analysis and will not be used for analysis in this Proposed Determination).[2] The 2015 GHG certification data included (by individual vehicle model produced in MY2015): vehicle production volume, carbon dioxide emissions rating for GHG certification, fuel type, fuel injection type, EGR, number of engine cylinders, displacement, intake valves per cylinder, exhaust valves per cylinder, variable valve timing, variable valve lift, engine cycle, cylinder deactivation, transmission type, drive type (rear-wheel, all-wheel, etc.), hybrid type (if applicable), and aspiration (naturally-aspirated, turbocharged, etc.). In addition, as noted above, EPA augmented the 2015 GHG certification and fuel economy database (the EPA "Verify" database) with publicly-available data which includes valve train information from Ward's Automotive Group, and data from NHTSA's MY2015 Draft TAR Volpe Baseline.

The process by which EPA created the 2015 baseline fleet Excel file is similar to the process used to create the 2014 MY baseline fleet Excel file for the Draft TAR. EPA created the baseline using 2015 GHG certification data from EPA's Verify database. In the past, the data in Verify did not include vehicle footprint data. Verify now includes a complete set of footprint data for each vehicle; however, it is separate from the GHG information. Manufacturers are required to report the numbers of each vehicle produced with a given footprint so the CO_2 target for that vehicle can be calculated. Separately, manufacturers are required to report the number of each unique combination of vehicle, engine, transmission, and driveline (two-wheel drive vs. four-wheel drive) that is produced along with its measured GHG information. The combination of the two sets of data are used to determine if a manufacturer is complying with the GHG standards. These two data sets, along with the valve train and engine cam information obtained from Wards Automotive and the curb weight and power steering information from NHTSA's 2015 Volpe fleet file, were combined into a single data set and used to create the 2015 baseline. Together, these sources inform the number of individual models, the volumes associated with each model, the CO_2-reducing technologies with which the models are equipped, and the model's current CO_2 emissions performance. This process creates a complete baseline fleet that can then be used to project the reference fleet as well as other fleets used in exploration of various scenarios in the OMEGA analysis.

Once a complete baseline fleet is created, the next step is to estimate the volumes and sales mix of vehicles out to 2025, which we refer to as the reference fleet volumes (see Chapters 1.1.3.1 and 1.1.3.1.1 below). In addition to the information just described used to create the 2015 baseline fleet, EPA used volume projections from both EIA's Annual Energy Outlook (AEO) 2016 and IHS-Polk, to generate the reference fleet volumes. Figure 1.2 shows the process for combining the six data sets, with the result being the completed baseline, with reference fleet projections.

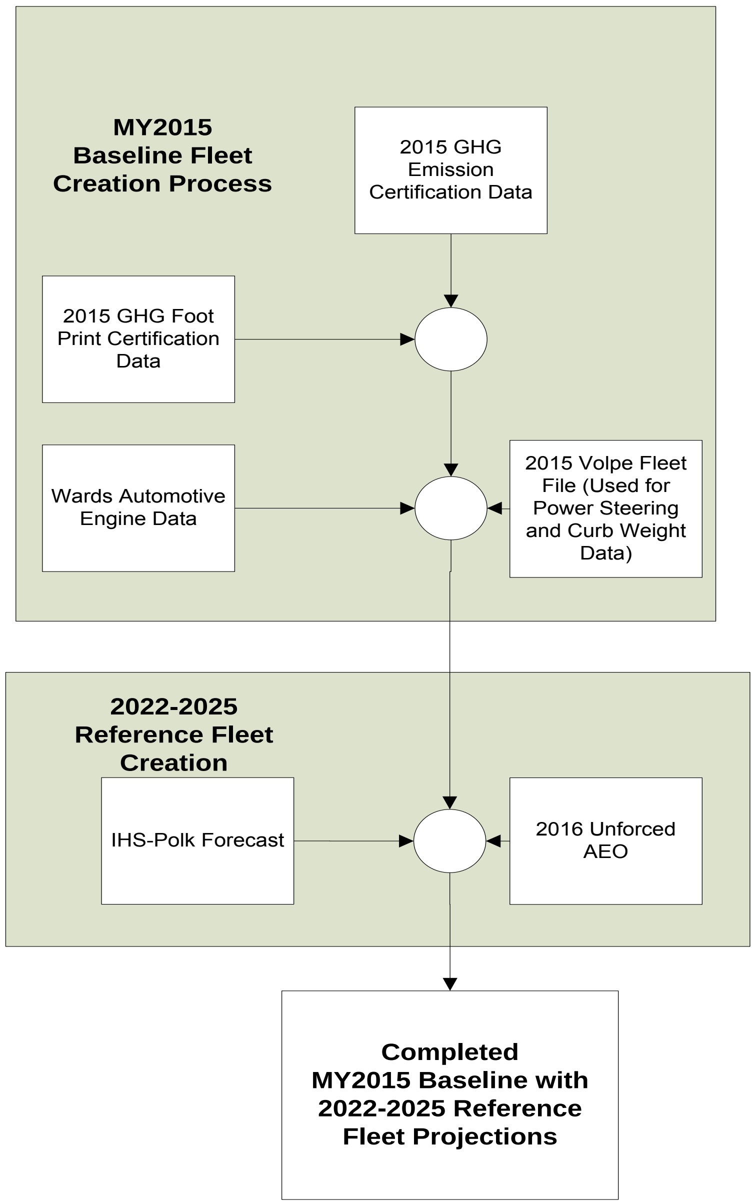


Figure 1.2 Process Flow for Creating the Baseline and Reference Fleet.

EPA contracted with IHS-Polk to produce an updated long range forecast of volumes for the future fleet for the Draft TAR, and is using these same data for this Proposed Determination. A detailed discussion of the method used to project the future fleet volumes can be found in Section 1.1.3.1.1 of this chapter.

EPA used the previously mentioned data to populate input files for the OMEGA model. The baseline Excel file is available in the docket.[3] The Data Definitions tab of the Excel file has a list of the columns of Data Tab. The column list has units, definition, and data source for each item that was compiled for the baseline data.

Table 1.1 displays the engine technologies present in the MY2015 baseline fleet. As previously described, this data was sourced primarily from the 2015 certification data, supplemented by Wards' data on utilization of cam technology.

Table 1.1 MY2015 Engine Technology Penetration

Manufacturers	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Over Head Cam	Over Head Cam	Variable Valve Timing Continuous Intake Only	Variable Valve Timing Discrete	Variable Valve Discrete Lift Only	Variable Valve Lift and Timing Discrete	Vehicles without Variable Valve Timing or Lift	Cylinder Deactivation	Direct Injection
All	Both	16%	1%	6%	85%	8%	8%	71%	0%	18%	3%	11%	43%
All	Cars	18%	1%	7%	91%	1%	1%	74%	0%	23%	2%	2%	45%
All	Trucks	13%	1%	5%	77%	17%	17%	68%	0%	12%	3%	22%	40%
Aston Martin	Cars	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	95%	0%	2%	97%	0%	0%	1%	0%	95%	4%	0%	95%
BMW	Trucks	100%	0%	0%	100%	0%	0%	7%	0%	82%	11%	0%	100%
FCA	Cars	4%	1%	6%	86%	8%	8%	41%	0%	51%	1%	5%	2%
FCA	Trucks	3%	0%	1%	83%	16%	15%	74%	0%	8%	3%	16%	0%
Ferrari	Cars	32%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	100%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	33%	0%	0%	100%	0%	0%	98%	0%	0%	2%	0%	50%
Ford	Trucks	53%	0%	0%	100%	0%	0%	84%	0%	0%	16%	0%	53%
GM	Cars	21%	1%	0%	96%	4%	3%	78%	0%	18%	1%	3%	71%
GM	Trucks	3%	0%	0%	33%	67%	67%	33%	0%	0%	0%	66%	97%
Honda	Trucks	0%	0%	56%	44%	0%	0%	0%	0%	100%	0%	56%	52%
Honda	Cars	0%	0%	54%	46%	0%	0%	0%	0%	100%	0%	12%	55%
Hyundai/Kia	Trucks	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	100%
Hyundai/Kia	Cars	6%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	82%
JLR	Cars	16%	82%	0%	100%	0%	0%	97%	0%	3%	0%	0%	100%
JLR	Trucks	35%	65%	0%	100%	0%	0%	80%	0%	20%	0%	0%	100%
Lotus	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	98%
Mazda	Trucks	0%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	66%
McLaren	Cars	100%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%

McLaren	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mercedes	Cars	79%	0%	0%	99%	0%	0%	98%	0%	0%	2%	0%	95%
Mercedes	Trucks	49%	0%	2%	98%	0%	0%	94%	0%	0%	6%	0%	98%
Mitsubishi	Cars	4%	0%	61%	39%	0%	0%	100%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	100%	0%	0%	0%	67%	6%	28%	0%	0%	0%
Nissan	Cars	3%	0%	0%	97%	0%	0%	91%	0%	7%	3%	0%	2%
Nissan	Trucks	0%	0%	0%	100%	0%	0%	96%	0%	4%	0%	0%	4%
Subaru	Cars	19%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	14%
Subaru	Trucks	3%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	3%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	2%	0%	0%	100%	0%	0%	99%	0%	1%	1%	0%	3%
Toyota	Trucks	1%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
Volkswagen	Cars	83%	4%	8%	92%	0%	0%	48%	0%	29%	23%	1%	91%
Volkswagen	Trucks	68%	30%	0%	100%	0%	0%	31%	0%	53%	16%	0%	100%
Volvo	Cars	100%	6%	0%	100%	0%	0%	100%	0%	0%	0%	0%	74%
Volvo	Trucks	90%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%

The data in Table 1.1 indicate that the MY2015 baseline fleet includes a significant amount of engine technology that has been added by manufacturers. For example, BMW stands out as having a significant number of gasoline turbocharged direct injection engines. Most of the fleet's engines are using DOHC (dual overhead cam), and have discrete variable valve timing (VVT). Over half of Honda's and GM"s Trucks all have engines with cylinder deactivation.

The data in Table 1.2 show the differences between the 2015 engine technology penetrations and the 2008 engine technology penetrations. To increase fuel economy, manufacturers applied considerable technology between 2008 and 2015. Manufacturers increased the use of direct injection 38 percent on cars and 37 percent on trucks. Manufacturers also increased the use of turbo chargers by 14 percent on cars and 12 percent on trucks.

Table 1.2 Change (2015-2008) in Engine Technology Penetration

Manufacturers	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Over Head Cam	Over Head Cam	Variable Valve Timing Continuous Intake Only	Variable Valve Timing Discrete	Variable Valve Discrete Lift Only	Variable Valve Lift and Timing Discrete	Vehicles without Variable Valve Timing or Lift	Cylinder Deactivation	Direct Injection
All	Both	13%	1%	-14%	23%	-9%	0%	51%	-9%	15%	-58%	4%	37%
All	Cars	14%	0%	-10%	18%	-8%	-8%	53%	-9%	19%	-55%	0%	38%
All	Trucks	12%	1%	-19%	30%	-12%	11%	50%	-9%	10%	-62%	10%	37%
Aston Martin	Cars	0%	0%	0%	0%	0%	0%	24%	0%	-24%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	62%	-1%	-12%	11%	0%	-2%	-84%	0%	82%	4%	0%	62%
BMW	Trucks	95%	0%	0%	0%	0%	0%	-93%	0%	82%	11%	0%	94%
FCA	Cars	3%	1%	-15%	14%	0%	8%	-1%	0%	50%	-57%	0%	2%
FCA	Trucks	3%	0%	-38%	79%	-41%	15%	70%	0%	8%	-93%	11%	0%
Ferrari	Cars	32%	0%	0%	0%	0%	0%	29%	0%	-29%	0%	0%	100%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	33%	-1%	-15%	15%	0%	-4%	98%	0%	0%	-94%	0%	50%
Ford	Trucks	53%	0%	-65%	68%	-3%	-28%	83%	0%	0%	-55%	0%	53%
GM	Cars	20%	1%	0%	40%	-40%	-26%	47%	0%	18%	-39%	-1%	65%
GM	Trucks	3%	0%	0%	3%	-3%	61%	16%	0%	0%	-78%	26%	97%
Honda	Trucks	-4%	0%	-8%	8%	0%	0%	0%	-96%	96%	0%	56%	48%
Honda	Cars	0%	0%	-4%	4%	0%	0%	0%	-73%	73%	0%	1%	55%
Hyundai/Kia	Trucks	0%	0%	0%	0%	0%	0%	100%	0%	0%	-100%	0%	100%
Hyundai/Kia	Cars	6%	0%	0%	0%	0%	0%	100%	0%	0%	-100%	0%	82%
JLR	Cars	16%	82%	0%	0%	0%	0%	22%	0%	3%	-24%	0%	100%
JLR	Trucks	35%	44%	0%	0%	0%	0%	80%	0%	20%	-100%	0%	100%
Lotus	Cars	0%	-77%	0%	-100%	0%	0%	-100%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	-11%	0%	0%	1%	0%	0%	93%	0%	0%	-93%	0%	86%
Mazda	Trucks	-24%	0%	-1%	1%	0%	0%	87%	0%	0%	-87%	0%	42%
McLaren	Cars	100%	0%	0%	100%	0%	0%	100%	0%	0%	0%	0%	0%
McLaren	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mercedes	Cars	77%	0%	-54%	53%	0%	-72%	94%	0%	0%	-22%	0%	93%
Mercedes	Trucks	34%	-1%	-35%	35%	0%	-35%	77%	0%	0%	-42%	0%	83%
Mitsubishi	Cars	-2%	0%	-39%	39%	0%	-100%	100%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	0%	0%	0%	-38%	67%	6%	28%	-62%	0%	0%
Nissan	Cars	3%	0%	0%	-3%	0%	0%	87%	0%	7%	-93%	0%	2%
Nissan	Trucks	0%	0%	0%	0%	0%	0%	96%	0%	4%	-100%	0%	4%
Subaru	Cars	5%	0%	-69%	69%	0%	0%	100%	-1%	0%	-99%	0%	14%
Subaru	Trucks	0%	0%	-70%	70%	0%	0%	100%	-5%	-23%	-73%	0%	3%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	2%	0%	0%	0%	0%	0%	70%	0%	1%	-71%	0%	-5%
Toyota	Trucks	1%	0%	0%	0%	0%	0%	39%	0%	0%	-39%	0%	-6%
Volkswagen	Cars	42%	4%	-71%	70%	0%	0%	-2%	0%	28%	-27%	1%	7%
Volkswagen	Trucks	63%	30%	0%	0%	0%	0%	19%	0%	-34%	15%	0%	0%
Volvo	Cars	51%	6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	74%
Volvo	Trucks	90%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

1.1.3.1 MY2015-Based MYs 2022-2025 Reference Fleet

This section provides further detail on the projection of the MY2015 baseline volumes into the MYs 2022-2025 reference fleet. It also describes more of the data contained in the baseline spreadsheet.

The reference fleet aims to reflect our latest projections about the market and fleet characteristics during MYs 2022 to 2025. Fundamentally, constructing this fleet involved projecting the MY2015 baseline fleet volumes out to MYs 2022-2025. It also included the assumption that none of the vehicle models changed during this period. Such projections, of course, have inherent uncertainties. However, as with the MY2008-based MY2022-2025 reference fleet used in the 2012 FRM, EPA relied on many sources of reputable information to make these projections, and regards the projections as reasonable notwithstanding the unavoidable uncertainties involved. No comments were received on EPA's use of IHS-Polk or the process for developing the future volumes for vehicles.

1.1.3.1.1 On What Data are EPA's Reference Vehicle Fleet Volumes Based?

EPA has based the projection of total car and light truck sales on the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2016, which was the most recent projection available at the time the Proposed Determination analysis was conducted. EIA's AEO 2016 also projects future energy production, consumption and prices.[4] EIA issued the final projection for AEO 2016 in July of 2016. As in the past analyses (MYs 2017-2025 rulemaking and the Draft TAR), AEO 2016 used the EIA's National Energy Modeling System (NEMS) to estimate the future relative market shares of passenger cars and light trucks. However, in NEMS, EIA models the light-duty fleet to comply with CAFE and GHG standards from 2012 through 2025. In order to create a reference fleet absent the effect of the 2022-2025 GHG standards, EPA only wanted NEMS to modify the fleet up to MY2021. Therefore, for the current analysis, EPA requested that EIA develop a new projection of passenger car and light truck sales shares by using NEMS to run scenarios from AEO 2016 cases (reference, high, and low), holding post-2021 CAFE and GHG standards constant at MY2021 levels. EIA created this special case for EPA.[5] The output from the NEMS model that EIA supplied is consistent with AEO 2016 since it has the same inputs as AEO 2016 with the exception of the standards being held constant after MY2021. As with the comparable exercise for the 2012 FRM baseline fleet, this case is referred to as the "Unforced Reference Case," and the values are shown below in Table 1.3. The "unforced reference case" will be referred to as "unforced AEO 2016" for the rest of this Technical Support Document (TSD). Table 1.4 shows the originally published AEO 2016 fleet projections. The total shift between cars and trucks is less than 1 percent of the total fleet volume in the rulemaking years.

Table 1.3 AEO 2016 Unforced Reference Case Values used in the MY2015 Based Market Fleet Projection

Model Year	Cars	Trucks	Total Vehicles
2021	8,136,902	7,929,520	16,066,421
2022	8,222,542	7,812,037	16,034,579
2023	8,478,234	7,783,396	16,261,630
2024	8,583,611	7,719,964	16,303,575
2025	8,715,199	7,715,601	16,430,800

Table 1.4 AEO 2016 Reference Case Values

Model Year	Cars	Trucks	Total Vehicles
2021	8,136,992	7,929,428	16,066,420
2022	8,222,617	7,811,960	16,034,578
2023	8,414,993	7,846,637	16,261,630
2024	8,467,865	7,835,709	16,303,575
2025	8,596,806	7,833,993	16,430,799

In 2021, car and light truck sales are projected to be 8.1 and 7.9 million units, respectively. While the total sales level of 16 million units is similar to pre-2008 levels, the fraction of car sales in 2021 and beyond is projected to be lower than in some of the previous AEO projections. This is consistent with the results in the Draft TAR using AEO2015. See Draft TAR at p. 4-10.

In addition, sales for segments within both the car and truck markets have already been changing, and this trend is expected to continue based on the projection from both IHS-Polk and EIA. In order to reflect these changes in fleet makeup, EPA used a custom long-range forecast purchased from IHS-Polk Automotive ("IHS-Polk").[E] IHS-Polk is a well-known industry analysis source for forecasting and other data (such as vehicle registration data). For several reasons, EPA decided to use the same forecast from IHS-Polk that was used for the Draft TAR (which IHS-Polk created based on AEO2015) for the MY2015-based market forecast. First, as just explained, AEO 2016's reference case is less than one percent different from AEO 2015 in the rulemaking years. Second, IHS-Polk uses a bottom-up approach (e.g., looking at the number of plants and capacity for specific engines, transmissions, vehicles, and registration data from Polk) for their forecast, which we believe is a robust forecasting approach. Third, IHS-Polk agreed to allow EPA to publish their entire forecast in the public domain (important for reasons of transparency). Fourth, the IHS-Polk forecast covered the time frame of greatest relevance to this analysis (the 2022-2025 model years). Fifth, it provided projections of vehicle sales both by manufacturer and by market segment. Finally, it utilized market segments similar to those used in the EPA emission certification program and fuel economy guide, such that EPA could include only the segment types covered by the light-duty vehicle standards.

The custom forecast which IHS-Polk created for EPA covers model years 2012-2030. Since EPA is using this forecast to generate the reference fleet volumes for this Proposed Determination (i.e., the fleet expected to be sold absent any increases in the stringency of the regulations after the 2021 model year), it is obviously important for the forecast to be independent of any such stringency increases. IHS-Polk does not normally use the GHG (or CAFE) standards as an input to their model, and EPA specified that they assume that the standard stringencies would stay constant at 2021 levels in the 2022-2025 time frame for our forecast. In addition, EPA specified that the IHS-Polk forecast use EIA's AEO 2015 fuel prices and economic indicators to create the forecast.

[E] IHS bought CSM from which we previously purchased a long range forecast. IHS also purchased Polk automotive which has registration data for all the vehicles in the United States.

Table 1.5 shows the AEO 2015 and AEO 2016 fuel prices and differences. EPA believes that the reference case fuel price (one to two cents per gallon) are close enough to justify continuing to use IHS-Polk's forecast. IHS-Polk uses many additional inputs in their model, including GDP growth, interest rates, the unemployment rate, and crude oil prices, to determine overall demand. They then use vehicle size, price, and function to forecast with enough resolution to predict brand and fleet segmentation. Additional details regarding the IHS-Polk forecast can be found in a methodology description provided by IHS-Polk to EPA which is available in the docket (EPA-HQ-OAR-2015-0827).

Table 1.5 AEO 2015 and AEO 2016 Reference Case Fuel Prices

	Fuel Price (dollars/gal)				
	2021	**2022**	**2023**	**2024**	**2025**
2016 AEO Fuel Price Reference case	$ 3.19	$ 3.31	$ 3.43	$ 3.53	$ 3.64
2015 AEO Fuel Price Reference case	$ 3.21	$ 3.30	$ 3.41	$ 3.52	$ 3.63
Difference 2016-2015	-$ 0.02	$ 0.01	$ 0.02	$ 0.01	$ 0.01

EPA combined the IHS-Polk forecast with data from other sources to create the 2015 baseline reference fleet projections. This process is discussed in the sections that follow. No commenters challenged the validity of IHS-Polk's projections, or their use by EPA for this purpose.

1.1.3.1.2 How did EPA develop the MY2015 Baseline and MYs 2022-2025 Reference Vehicle Fleet Volumes?

The process of producing the MY2015 baseline and 2022-2025 reference fleet volumes involved combining the baseline fleet with the projection data described above. This complex multi-step procedure is described in this section. The procedure is unchanged from the Draft TAR.

1.1.3.1.3 How was the MY2015 Baseline Data Merged with the IHS-Polk Data?

EPA used the same method as in the Draft TAR for mapping certification vehicles to IHS-Polk vehicles. See Draft TAR Chapter 4.1.2.1.4. Merging the 2015 baseline data with the 2022-2025 IHS-Polk data required a thorough mapping of certification vehicles to IHS-Polk vehicles by individual make and model. One challenge that EPA faced when determining a reference case fleet was that the market segmentation of the sales data projected by IHS-Polk was similar but different from the segmentation used in EPA's Verify database. In order to create a common segmentation between the two databases, EPA performed a side-by-side comparison of each vehicle model in both data sets, and created an additional "IHS-Polk Class" modifier in the baseline spreadsheet to map the two data sets together. EPA then projected the reference fleet volumes based on the "IHS-Polk Class."

The baseline data and reference fleet volumes are available to the public. The baseline Excel spreadsheet that is available in the Docket is the result of the merged files.[6] The spreadsheet provides specific details on the sources and definitions for the data. The baseline Excel file includes the following tabs: "Data," "Data Definition," "Platforms," "VehType," "Lookups," "Metrics," "Machine," "MarketFile," and "Safety." The "Data" tab contains the raw data. In the "Data Definition" tab, each column is defined and its data source is named.

In the combined EPA certification and IHS-Polk data, all MY2015 vehicle models are assumed to continue out to 2025, although their volumes change in proportion to IHS-Polk projections. As explained in the following subsection, this methodology is used to provide surrogate greenhouse gas performance data for new emerging models. As a result, new models expected to be introduced within the 2015-2025 time frame are mapped to existing models. Remapping the volumes from these new vehicles to the existing models via manufacturer segments preserves the overall fleet volume. All MYs 2022-2025 vehicles are mapped from the existing vehicles to the manufacturer's future segment volumes. The mappings are discussed in the next section. Further discussion of this limitation is discussed below in Chapter 1.1.3.1.4. The statistics of this fleet will be presented after the mapping since further volume modifications were required.

1.1.3.1.4 How were the IHS-Polk Forecast and the Unforced AEO 2015 Forecast Used to Project the Future Fleet Volumes?

The next step in EPA's generation of the reference fleet is one of the more complicated steps to explain (although we note that EPA utilized a similar methodology in preparing both the MY2008 baseline (for the 2022-2025 reference fleet) and an identical methodology creating the MY2014 baseline fleet in the Draft TAR).

First, each vehicle in the 2015 data had an IHS-Polk segment mapped to it. Second, EPA compared the breakdown of segment volumes by manufacturer between the IHS-Polk and 2015 data set. Third, a correction was applied for Class 2B vehicles in the IHS-Polk data. Fourth, the individual manufacturer segment multipliers were created by year. And finally, the absolute volumes of cars and trucks were normalized (set equal) to the total sales estimates of the unforced AEO 2016. This final step is required to create a fleet forecast that reflects the official government forecast for future vehicle sales. The unforced AEO 2016 forecast alone does not have the necessary resolution, down to the vehicle segment level, for EPA to perform its analysis. Therefore, EPA applies both the purchased forecast from IHS-Polk and the unforced AEO 2016 forecast to create a complete fleet forecast.

The process started with mapping the IHS-Polk segments to each vehicle in the baseline data. The mapping required determination of the IHS-Polk segment by lookup at each of the 2,653 baseline vehicles in the IHS-Polk forecast (which has only 617 vehicles since they do not forecast powertrain or footprint differences), and labeling it in the "IHS-Polk Class" column of the baseline data. The IHS-Polk data has 52 segments. Table 1.6 lists the IHS-Polk segments for reference. Table 1.7 shows some of the Honda vehicles in the GHG data with their "IHS-Polk Segment" identified.

Table 1.6 List of IHS-Polk Segments

IHS-Polk Segments		
Micro Non-premium Car	Compact Non-premium Car	Mid-Size Premium Van
Micro Non-premium Sporty	Compact Non-premium MPV	Mid-Size Super Premium Car
Mini Non-premium Car	Compact Non-premium Sporty	Mid-Size Super Premium Sporty
Mini Non-premium MPV	Compact Non-premium SUV	Mid-Size Super Premium SUV
Mini Non-premium Sporty	Compact Non-premium Van	Full-Size Non-premium Car
Mini Non-premium SUV	Compact Premium Car	Full-Size Non-premium Pickup
Mini Premium Car	Compact Premium Sporty	Full-Size Non-premium Sporty
Mini Premium Sporty	Compact Premium SUV	Full-Size Non-premium SUV
Subcompact Non-premium Car	Compact Super Premium Sporty	Full-Size Non-premium Van
Subcompact Non-premium MPV	Compact Super Premium SUV	Full-Size Premium Car
Subcompact Non-premium Pickup	Mid-Size Non-premium Car	Full-Size Premium Sporty
Subcompact Non-premium Sporty	Mid-Size Non-premium MPV	Full-Size Premium SUV
Subcompact Non-premium SUV	Mid-Size Non-premium Pickup	Full-Size Premium Van
Subcompact Premium Car	Mid-Size Non-premium Sporty	Full-Size Super Premium Car
Subcompact Premium MPV	Mid-Size Non-premium SUV	Full-Size Super Premium Sporty
Subcompact Premium Sporty	Mid-Size Premium Car	Full-Size Super Premium SUV
Subcompact Premium SUV	Mid-Size Premium Sporty	
Subcompact Super Premium Sporty	Mid-Size Premium SUV	

Table 1.7 Example of Honda Vehicles Being Mapped to Segments Based On the IHS-Polk Forecast

Manufacturer	Name Plate	Model	IHS-Polk Segment
Honda	Acura	ILX	Compact Premium Car
Honda	Acura	MDX	Mid-Size Premium SUV
Honda	Acura	RDX	Compact Premium SUV
Honda	Acura	RLX	Mid-Size Premium Car
Honda	Acura	TSX	Mid-Size Premium Car
Honda	Honda	ACCORD	Mid-Size Non-Premium Sporty
Honda	Honda	ACCORD	Mid-Size Non-Premium Car
Honda	Honda	CIVIC	Compact Non-Premium Car
Honda	Honda	CIVIC	Compact Non-Premium Sporty
Honda	Honda	FCX	Compact Non-Premium Car
Honda	Honda	CR-V	Compact Non-Premium SUV
Honda	Honda	CR-Z	Mini Non-Premium Sporty
Honda	Honda	CROSSTOUR	Mid-Size Non-Premium SUV
Honda	Honda	FIT	Subcompact Non-Premium Car
Honda	Honda	INSIGHT	Compact Non-Premium Car
Honda	Honda	ODYSSEY	Mid-Size Non-Premium MPV
Honda	Honda	PILOT	Mid-Size Non-Premium SUV
Honda	Honda	RIDGELINE	Mid-Size Non-Premium Pickup Truck

In the next step, segment volume by manufacturer was compared between the baseline and IHS-Polk data sets. This is necessary to determine if all of the segments a manufacturer will produce in the future are currently represented by the 2015 certification data. The forecasts used in past rulemakings predicted very few new segments for manufacturers. The new forecast from IHS-Polk projects that manufacturers will be entering more new segments (i.e., segments they currently do not participate in) than in previous forecasts. This requires making sure a manufacturer's volume in the new segment will be added to the volume of a manufacturer's closest existing segment. The flow chart below (Figure 1.3) shows the process for determining this "closest class." This process worked well for the majority of manufacturers.[F] We believe that this process of establishing "closest class" surrogates provides the best estimate of the potential current performance of a given vehicle type and the technology that will be required to meet the 2025 standards.

[F] The exceptions were Tesla and Aston Martin, both of which at the time operated only in the car segment and had not yet entered the SUV segment.

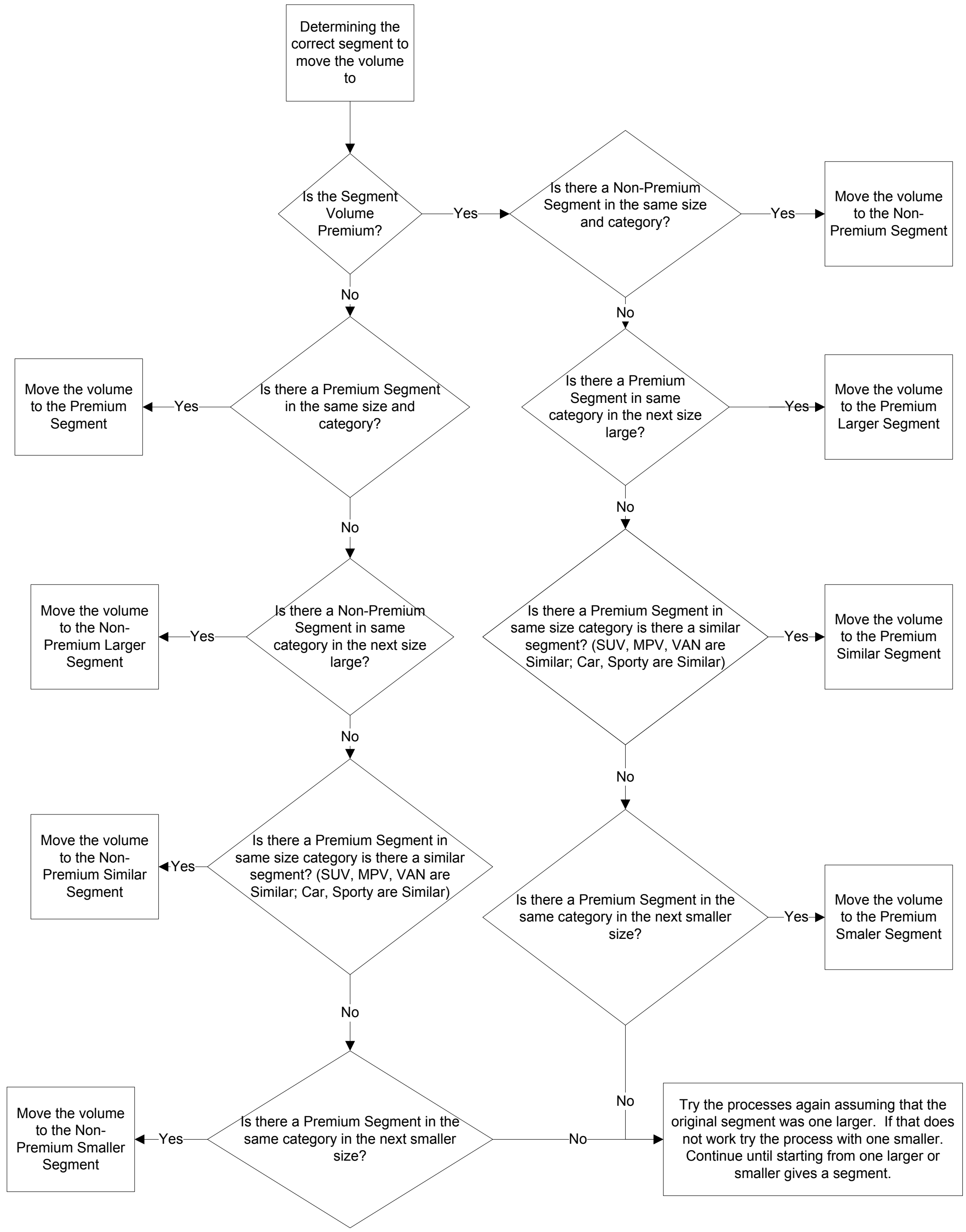


Figure 1.3 Process Flow for Determining where Segment Volume Should Move

Table 1.8 shows Honda's segments with their volumes for both the baseline data and IHS-Polk. Note that the segments “Compact Premium Sporty,” “Mid-Size Non-premium Pickup,” “Subcompact Non-premium SUV,” and “Subcompact Premium SUV” do not exist in the baseline data. The closest classes to those are “Compact Non-premium Car,” “Mid-Size Non-premium SUV,” and “Compact Non-premium SUV.”

It is also important to note the difference between model year (MY) and calendar year (CY) sales. MY sales can be shorter or longer than a full calendar year due to product launch and change decisions made by a manufacturer. As a result, the MY sales[G] can be less than or greater than a respective calendar year sales. Table 1.8 provides a manufacturer example. For CY2015, Honda introduced a new MY2016 Ridgeline pickup truck. Honda did not produce any pickup trucks for MY2015 so it was necessary to move Honda's truck volume to their next closest class, which is "Mid-Size Non-premium SUV." IHS shows that Honda built 515 "Mid-Size Non-premium Pickups" for 2015, but none of those were MY2015 vehicles. In years that are close to the baseline year, old models are exiting and new models are entering, which can be a source of error. But as years progress, CY and MY volumes become the same in a forecast, since the forecast neither adds nor deletes models. This allows EPA to use a CY forecast since we are concerned with vehicles being built far enough in the future that CY and MY volumes are approximately the same.

In comments on the Draft TAR, Honda commented that the Draft TAR figures for Honda vehicles appeared to be in error. On examination, EPA discovered that Honda Civic Coupes had been inadvertently classified as sedans, and Honda Civic Sedans had been classified as coupes. This caused Civic models to show the wrong volumes. EPA corrected this error when creating the 2015 baseline fleet for the current analysis.

Table 1.8 Example Honda 2015 Volumes by Segment from the IHS-Polk Forecast

Honda-Baseline Data	2015 MY	Honda-IHS-Polk Data	2015 CY[H]	2018 CY	Action
Compact Non-Premium Car	353,523	Compact Non-premium Car	337,423	358,046	
Compact Non-Premium SUV	359,785	Compact Non-premium SUV	351,827	299,644	
Compact Premium Car	11,093	Compact Premium Car	18,470	15,379	
		Compact Premium Sporty	0	797	Move Volume to Compact Premium Car
Compact Premium SUV	50,387	Compact Premium SUV	49,882	40,642	
Mid-Size Non-premium Car	354,428	Mid-Size Non-premium Car	349,921	338,848	
Mid-Size Non-Premium MPV	129,988	Mid-Size Non-premium MPV	124,107	106,887	
		Mid-Size Non-premium Pickup	515	52,244	Move Volume to Mid-Size Non-premium SUV
Mid-Size Non-Premium SUV	116,420	Mid-Size Non-premium SUV	141,796	144,182	
Mid-Size Premium Car	68,727	Mid-Size Premium Car	50,380	44,876	
Mid-Size Premium SUV	45,642	Mid-Size Premium SUV	59,742	53,249	
Mini Non-Premium Sporty	3,814	Mini Non-premium Sporty	3,283	10,915	
Subcompact Non-Premium Car	83,367	Subcompact Non-premium Car	60,246	54,988	Move Volume to Compact Non-Premium Car
		Subcompact Non-premium SUV	49,609	73,855	Move Volume to Compact Non-Premium SUV
		Subcompact Premium SUV	0	23,977	Move Volume to Compact Non-Premium SUV

[G] Model Year sales may begin as early as January 1 of the previous calendar year (MY - 1).
[H] 2015 Calendar Year can include both 2015 and 2016 Model Year vehicle sales if both are built in the calendar year.

A step that is related to the comparison step is the filtering of Class 3 vehicles from the IHS-Polk forecast. IHS-Polk includes Class 2b and Class 3 vehicles (vans and large pickup trucks) in its light-duty forecast. Class 2b vans with seating for multiple occupants are all appropriately classified as MDPVs (Medium Duty Passenger Vehicles) and must be included in the forecast since they are regulated under the light-duty GHG program. Class 2b large pickup trucks, however, are not regulated under the light-duty GHG program but under the medium-duty and heavy-duty fuel efficiency and GHG programs. See 76 FR 57120 and 81 FR 73729 (Oct. 25, 2016). These vehicles must therefore be removed from the forecast. Because IHS-Polk identifies the Class 2b and Class 3 pickup trucks with the label 'HD,' it was readily apparent which Class 2b pickup trucks to filter from the forecast. Vans in the IHS-Polk forecast, on the other hand, have both Class 2b and 3 and MDPVs in their totals, and so must have a correction factor applied. This is accomplished by creating a multiplier for each manufacturer's Full-Size Non-Premium Vans and applying it to each manufacturer's Full-Size Non-Premium Van volume every model year in the IHS-Polk forecast; specifically, by taking a manufacturer's 2015 model year Full-Size Non-Premium Van baseline volume and dividing by its 2015 calendar year Full-Size Non-Premium Van IHS-Polk volume. Table 1.9 shows the volumes and the resulting multiplier for FCA. Table 1.10 shows the 2025 IHS-Polk volume, the multiplier, and the result of applying the multiplier to the original volume for FCA.

Table 1.9 Example Values Used to Determine the MDPV Multiplier for FCA

Manufacturer	NEW SEGMENT	IHS-Polk 2015 Volume	2015 GHG Volume	MDPV Multiplier
FCA	Full-Size Non-Premium Van	21,125	11,632	0.55

Table 1.10 Example Values Used to Determine FCA's 2025 Van Volume

Manufacturer	NEW SEGMENT	Original 2025 Volume	MDPV Multiplier	2025 Volume after Multiplier
FCA	Full-Size Non-Premium Van	15,074	0.55	8,291

EPA next created individual manufacturer segment multipliers to be used with the individual 2015 vehicle volumes to create projections for the future fleet. The individual manufacturer segment multipliers are created by dividing each year of the IHS-Polk forecast's individual manufacturer segment volume by the manufacturer's individual segment volume, determined using 2015 data. Table 1.11 shows the 2015 Volume, the 2025 IHS-Polk Full-Size Non-Premium Van volume after Class 2b vehicles were removed, and the individual manufacturer volume for Full-Size Non-Premium Van. The multiplier is the result of dividing the 2025 volume by the 2015 volume.

Table 1.11 Example Values Used to Determine FCA 2025 Individual Full-Size Non-Premium Van Multiplier

Manufacturer	IHS-Polk Segment	2015 GHG Volume	2025 Volume after Multiplier	Fiat/Chrysler Individual Full-Size Non-Premium Van Multiplier for 2025
FCA	Full-Size Non-Premium Van	15,074	8,291	71.4%

Now that the individual manufacturer segment multipliers have been calculated, they can be applied to each vehicle in the 2015 data. The segment multipliers are applied by multiplying the 2015 volume for a vehicle by the multiplier for its manufacturer and segment. Table 1.12 shows the 2015 volumes, the individual manufacturer segment multipliers, and the result of multiplying the multiplier and the volume for 2025 project volumes for many of FCA's Full-Size Non-Premium Vans.

Table 1.12 Example Applying the Individual Full-Size Non-Premium Van Multiplier for FCA

Manufacturer	Model	IHS-Polk Segment	2015 GHG Volume	Fiat/Chrysler Individual Full-Size Non-Premium Van Multiplier for 2025	2025 Project Volume Before AEO Normalization
FCA	Cargo Van A	Full-Size Non-Premium Van	208	71.4%	148
FCA	Cargo Van B	Full-Size Non-Premium Van	5,712	71.4%	4,076

Normalizing to unforced AEO 2016 forecast for cars and trucks must be done once the individual manufacturer segment multipliers have been applied to all vehicles across every year (2011-2025) of the IHS-Polk forecast. In order to normalize a year, the number of trucks and the number of cars produced must be determined. Then, the truck and car totals from the unforced AEO 2016 are used to determine a normalizing multiplier. Table 1.13 shows the 2025 car and truck totals before normalization, the unforced AEO 2016 car and truck totals in 2025, and the multipliers, which are the result of dividing the unforced AEO 2016 totals by totals before normalization.

Table 1.13 Example Unforced AEO 2016 Truck and Car Multipliers in MY2025

Vehicle Type	2025 Total Before Normalization	2025 Total from AEO 2016	2025 Normalizing Multiplier
Cars	9,889,511	8,715,199	88%
Trucks	5,838,907	7,715,600	132%

The final step in creating the reference volumes is applying the unforced AEO multipliers. The AEO multipliers are applied by car/truck type. Table 1.14 shows the normalized volume, the unforced AEO 2016 truck multiplier for MY2025, and the final resulting volume for a number of FCA Full-Size Non-Premium Vans.

Table 1.14 Example Applying the Unforced AEO Truck Multiplier to FCA Full-Size Non-Premium Vans

Manufacturer	Model	C/T Type	2025 Project Volume Before Unforced AEO 2016 Normalization	Unforced AEO 2016 Truck Multiplier for 2025	2025 Project Volume with Unforced AEO 2016 Normalization
FCA	Cargo Van A	Truck	148	132%	196
FCA	Cargo Van B	Truck	4,076	132%	5,385

1.1.3.2 What Are the Sales Volumes and Characteristics of the MY2015 Based Reference Fleet?

Table 1.15 and Table 1.16 below contain the sales volumes that result from the process above for MY2015 and MYs 2021-2025. In Table 1.15, "SmallPickup" is zero. The only manufacturer that produced a small pickup in recent years was Honda, and Honda did not build a MY2015 Ridgeline.

Table 1.15 Vehicle Segment Volumes

Segment	Actual and Projected Sales Volume					
	2015	**2021**	**2022**	**2023**	**2024**	**2025**
SubCmpctAuto	990,135	879,310	907,553	967,714	967,714	973,176
CompactAuto	2,564,949	2,395,133	2,382,352	2,466,062	2,466,062	2,566,388
MidSizeAuto	3,905,449	2,860,094	2,916,546	2,980,777	2,980,777	3,073,007
LargeAuto	523,225	538,526	550,746	568,332	568,332	586,843
SmallPickup	-	-	-	-	-	-
LargePickup	1,786,223	1,875,652	1,815,030	1,815,163	1,815,163	1,843,621
SmallSuv	2,184,788	2,696,071	2,664,266	2,691,022	2,691,022	2,689,904
MidSizeSuv	2,204,122	2,159,523	2,132,377	2,153,164	2,153,164	2,133,971
LargeSuv	1,088,051	1,427,186	1,392,192	1,387,494	1,387,494	1,373,818
ExtraLargeSuv	920,239	717,693	728,207	684,299	684,299	662,595
MiniVan	548,342	494,165	518,402	519,562	519,562	497,794
CargoVan	20,876	23,068	26,907	28,042	28,042	29,683

Table 1.16 Car and Truck Volumes

Vehicle Type	Actual and Projected Sales Volume					
	2015	2021	2022	2023	2024	2025
Cars	9,597,936	8,136,902	8,222,542	8,478,234	8,583,611	8,715,199
Trucks	7,138,461	7,929,520	7,812,037	7,783,396	7,719,964	7,715,601
Cars and Trucks	16,736,397	16,066,421	16,034,579	16,261,630	16,303,575	16,430,800

Table 1.17 lists the sales volumes by manufacturer and C/T type for MY2015 and MY2021-2025. Lotus is a small volume manufacturer and chose not to build MY2015 vehicles.

Table 1.17 Car and Truck Definition Manufacturer Volumes

Manufacturers	C/T Type	2015 Baseline Sales	2021 Projected Volume	2022 Projected Volume	2023 Projected Volume	2024 Projected Volume	2025 Projected Volume
All	Both	16,736,397	16,066,421	16,034,579	16,261,630	16,303,575	16,430,800
All	Cars	9,597,936	8,136,902	8,222,542	8,478,234	8,583,611	8,715,199
All	Trucks	7,138,461	7,929,520	7,812,037	7,783,396	7,719,964	7,715,601
Aston Martin*	Cars	1,119	1,384	1,320	1,325	1,290	1,422
Aston Martin*	Trucks	-	-	-	-	-	-
BMW	Cars	338,704	317,648	332,266	350,651	357,144	348,293
BMW	Trucks	87,135	115,780	110,687	107,555	105,521	104,931
FCA	Cars	769,687	535,600	554,402	552,943	547,469	558,331
FCA	Trucks	1,416,487	1,270,099	1,261,444	1,267,012	1,256,467	1,275,022
Ferrari*	Cars	2,645	2,999	6,491	7,904	8,519	9,190
Ferrari*	Trucks	-	-	-	-	-	-
Ford	Cars	888,604	831,609	829,433	818,078	800,638	833,326
Ford	Trucks	972,891	1,256,726	1,243,115	1,226,286	1,204,489	1,182,848
GM	Cars	1,331,442	1,154,344	1,162,751	1,242,812	1,241,036	1,239,682
GM	Trucks	1,525,017	1,258,030	1,261,455	1,210,912	1,196,960	1,199,874
Honda	Cars	1,020,310	819,658	839,422	865,428	895,193	883,518
Honda	Trucks	556,864	861,851	857,929	869,110	853,349	836,097
Hyundai/Kia	Cars	1,228,399	1,129,153	1,138,735	1,157,423	1,168,074	1,185,878
Hyundai/Kia	Trucks	91,058	227,750	217,616	227,780	226,399	227,669
JLR	Cars	15,600	22,932	24,262	25,440	25,156	24,494
JLR	Trucks	54,435	102,505	100,010	96,409	95,196	94,350
Lotus*	Cars	-	-	-	-	-	-
Lotus*	Trucks	-	-	-	-	-	-
Mazda	Cars	207,100	212,725	212,269	210,091	217,939	225,981
Mazda	Trucks	78,793	129,877	135,392	139,357	135,675	136,192
McLaren*	Cars	625	941	1,045	1,199	1,372	1,336
McLaren*	Trucks	-	-	-	-	-	-
Mercedes	Cars	231,899	218,508	224,049	237,549	238,973	238,811
Mercedes	Trucks	123,727	178,096	172,461	168,875	167,255	166,733
Mitsubishi	Cars	91,822	47,775	50,602	55,964	60,376	61,002
Mitsubishi	Trucks	39,366	35,229	34,592	36,127	35,425	39,452
Nissan	Cars	1,216,392	820,204	816,918	861,832	864,924	895,430
Nissan	Trucks	481,583	579,939	563,728	544,882	540,234	551,676
Subaru	Cars	175,352	140,987	149,303	147,953	148,723	152,485
Subaru	Trucks	447,383	531,411	506,265	540,938	539,008	555,249
Tesla	Cars	24,322	90,547	88,844	99,390	102,654	109,459
Tesla	Trucks	-	-	-	-	-	-
Toyota	Cars	1,524,190	1,203,844	1,206,329	1,233,020	1,280,689	1,299,472
Toyota	Trucks	1,127,056	1,071,915	1,047,556	1,056,695	1,058,452	1,031,420
Volkswagen	Cars	487,108	541,520	540,983	567,019	581,817	599,186
Volkswagen	Trucks	112,382	261,463	249,199	244,025	259,817	265,166
Volvo	Cars	42,616	44,523	43,117	42,216	41,626	47,901
Volvo	Trucks	24,284	48,849	50,589	47,432	45,717	48,921

*Note: These manufacturers are shown here for reference but are not in the analysis in Chapter 5 or considered in the ZEV sales that are part of the analysis fleet as discussed in Chapter 1.2.1.

Table 1.18 shows how the change in fleet makeup may affect the footprint distributions over time. The resulting data indicate that the average vehicle footprint would not change significantly between 2015 and 2025.

Table 1.18 Production Weighted Foot Print Mean

Model Year	Average Footprint of all Vehicles	Average Footprint Cars	Average Footprint Trucks
2015	49.3	46.1	53.7
2017	49.8	46.0	53.0
2018	49.7	46.1	53.0
2019	49.7	46.1	53.0
2020	49.5	46.1	53.0
2021	49.5	46.1	53.0
2022	49.5	46.1	53.0
2023	49.4	46.0	52.9
2024	49.3	46.0	52.9
2025	49.3	46.1	53.0

Table 1.19 shows the projected changes in number of engine cylinders over the model years of the rule. The current assumptions indicate that the number of cylinders would shrink slightly between 2015 and 2019 for trucks and then remain relatively constant over the 2019-2025 time frame, with only a very slight shift to 4 cylinders in trucks (possibly due to an increase in the number of small SUVs).

Table 1.19 Percentages of 4, 6, and 8 Cylinder Engines by Model Year

	Trucks			Cars		
Model Year	4 Cylinders	6 Cylinders	8 Cylinders	4 Cylinders	6 Cylinders	8 Cylinders
2015	28.6%	50.3%	21.1%	81.1%	16.2%	2.7%
2017	31.5%	50.7%	17.8%	81.3%	15.8%	2.9%
2018	32.5%	49.7%	17.8%	80.7%	16.4%	2.9%
2019	33.0%	49.2%	17.8%	80.8%	16.4%	2.9%
2020	33.1%	49.1%	17.8%	81.0%	16.1%	2.9%
2021	33.2%	49.4%	17.5%	81.0%	16.0%	3.0%
2022	33.0%	49.7%	17.3%	80.7%	16.2%	3.1%
2023	33.6%	49.4%	17.0%	80.8%	16.2%	3.0%
2024	33.7%	49.3%	17.0%	80.9%	16.1%	3.0%
2025	33.8%	49.0%	17.2%	80.9%	16.1%	3.0%

1.1.3.3 What Are the Differences in the Sales Volumes and Characteristics of the MY2008-Based (FRM) and the MY2015-Based Reference Fleets?

This section compares some of the differences between the MY2008-based reference fleet used in previous analyses and the MY2015-based reference fleet used in the current analysis. The 2008 fleet projection is based on several sources: MY2008 certification data, a long range forecast provided by CSM, and interim unforced AEO 2011. The 2015 fleet projection is based on MY2015 certification data, a long-range forecast provided by IHS-Polk Automotive, and the unforced AEO 2016, as described earlier in this chapter. All tables in this section show the differences between the MY2008 and MY2015 fleets.

Table 1.20, Table 1.21, and Table 1.22 below show the sales volume differences between the two fleets, calculated by subtracting the MY2008-based fleet projection from the MY2015-based fleet projection. The sales in MY2015 were significantly higher (by 3,025,250 vehicles) than in MY2008, when sales may have been impacted by an economic recession. MY2015 volumes are also higher than forecast at the time of the FRM.

For 2015, there is an increase in the number of compact and midsize autos, large trucks, and all SUVs. For 2025, one of the biggest differences between the two forecasts is the number of cars, which in part seem to be replaced by small and midsize SUVs. The shift from cars to trucks is due to application of the unforced AEO 2016 data while the shifts within segments reflect the data from the IHS-Polk forecast.

Table 1.20 Differences in Vehicle Segment Volumes

Reference Class Segment	Actual Sales Volume	Difference in Projected Sales Volume				
	2015-2008	2021	2022	2023	2024	2025
SubCmpctAuto	-306,978	-1,657,574	-1,688,249	-1,660,379	-1,734,262	-1,808,385
CompactAuto	603,852	-107,830	-191,482	-147,905	-259,283	-257,112
MidSizeAuto	813,354	-573,597	-623,142	-702,899	-761,429	-732,487
LargeAuto	-42,851	152,870	186,900	199,948	206,089	211,829
SmallPickup	-177,497	-150,123	-147,138	-151,315	-154,627	-154,838
LargePickup	221,780	522,791	480,262	527,579	556,971	596,868
SmallSuv	575,990	1,143,916	1,107,175	1,147,906	1,117,851	1,101,240
MidSizeSuv	912,792	722,167	692,742	715,745	699,660	671,233
LargeSuv	437,341	363,099	310,474	282,426	224,914	182,174
ExtraLargeSuv	171,164	25,363	7,251	-64,288	-50,488	-78,501
MiniVan	-171,187	-351,891	-331,269	-329,887	-311,176	-341,658
CargoVan	-12,508	-70,492	-65,216	-64,878	-58,841	-58,889

Table 1.21 Differences in Actual and Projected Sales Volumes between MY2015 and MY2008 fleets

C/T Type	Difference in Actual Sales Volume	Difference in Projected Sales Volume				
	2015 - 2008	2021	2022	2023	2024	2025
Cars	1,468,413	-2,251,245	-2,393,927	-2,368,096	-2,551,279	-2,700,077
Trucks	1,556,837	2,269,945	2,132,236	2,120,147	2,068,602	2,031,550
Cars and Trucks	3,025,250	18,700	-261,691	-247,948	-482,677	-668,527

Table 1.22 below shows the differences in sales volumes by manufacturer and car/truck type between the MY2008-based fleet and the MY2015-based fleet. The manufacturers with the next largest increases in sales in MY2015 (from MY2008) are FCA, Ford, Hyundai/Kia, Nissan, Subaru, and Toyota. The manufacturers with a net decrease in sales in MY2015 (from MY2008) are Aston Martin, Honda, GM, Mazda, Mitsubishi, and Volvo. The manufacturers with the next largest increases in sales in MY2025 are FCA, Subaru, and Tesla. The manufacturers forecast to have a significant net decrease in sales in MY2025 are GM, Mazda, and Volvo. Table 1.22 also shows a projected decrease in the total vehicle market in MY2025 by 668,527 vehicles.

Table 1.22 Differences in Sales Volumes by Manufacturer and Car/Truck Type between MY2008-based and MY2015-based fleets

Manufacturers	Segment Type	2015-2008 Difference in Sales	2021 Difference in Volume	2022 Difference in Volume	2023 Difference in Volume	2024 Difference in Volume	2025 Difference in Volume
All	Both	3,025,250	18,700	-261,691	-247,948	-482,677	-668,527
All	Cars	1,468,413	-2,251,245	-2,393,927	-2,368,096	-2,551,279	-2,700,077
All	Trucks	1,556,837	2,269,945	2,132,236	2,120,147	2,068,602	2,031,550
Aston Martin	Cars	-251	326	271	284	149	240
Aston Martin	Trucks	0	0	0	0	0	0
BMW	Cars	46,908	-41,450	-27,768	-9,911	-31,050	-56,963
BMW	Trucks	25,811	-12,944	-18,211	-19,966	-41,005	-40,478
FCA	Cars	66,529	114,587	130,229	129,061	121,452	121,852
FCA	Trucks	459,695	921,486	898,435	905,949	911,505	943,261
Ferrari	Cars	1,195	-4,059	-647	677	1,078	1,532
Ferrari	Trucks	0	0	0	0	0	0
Ford	Cars	-68,095	-570,009	-585,788	-656,719	-703,032	-706,784
Ford	Trucks	158,697	542,545	528,849	526,281	515,635	498,372
GM	Cars	-255,949	-409,932	-415,805	-363,683	-395,769	-434,253
GM	Trucks	17,220	-271,990	-246,198	-285,906	-296,637	-324,134
Honda	Cars	13,671	-379,222	-398,082	-400,136	-412,658	-456,803
Honda	Trucks	51,724	325,935	318,695	332,212	316,355	278,400
Hyundai/Kia	Cars	668,550	184,479	171,669	180,369	158,483	145,845
Hyundai/Kia	Trucks	-21,572	-24,148	-34,572	-29,097	-35,812	-38,120
JLR	Cars	6,004	-35,745	-35,087	-35,200	-38,572	-40,923
JLR	Trucks	-1,149	44,352	41,420	37,543	37,215	37,544
Lotus	Cars	-252	-278	-290	-299	-308	-316

Lotus	Trucks	0	0	0	0	0	0
Mazda	Cars	-39,561	-62,015	-68,882	-86,818	-82,676	-80,823
Mazda	Trucks	22,908	70,650	75,085	77,391	73,705	74,824
McLaren	Cars	625	941	1,045	1,199	1,372	1,336
McLaren	Trucks	0	0	0	0	0	0
Mercedes	Cars	23,704	-81,870	-80,689	-74,958	-93,364	-101,907
Mercedes	Trucks	44,592	78,647	71,526	63,561	60,171	65,666
Mitsubishi	Cars	6,464	-18,076	-16,659	-11,716	-10,352	-12,303
Mitsubishi	Trucks	23,995	-80	-635	657	-577	3,066
Nissan	Cars	498,523	-92,425	-120,529	-92,508	-117,848	-119,345
Nissan	Trucks	176,037	171,910	151,844	127,761	118,018	125,221
Subaru	Cars	59,317	-89,794	-89,310	-93,659	-99,560	-104,486
Subaru	Trucks	364,837	458,638	433,528	467,917	464,865	480,528
Tesla	Cars	23,522	61,924	60,475	71,240	71,792	77,485
Tesla	Trucks	0	0	0	0	0	0
Toyota	Cars	266,609	-694,059	-773,704	-797,805	-793,547	-802,220
Toyota	Trucks	175,920	-143,624	-187,497	-168,285	-149,561	-178,596
Volkswagen	Cars	173,933	-86,364	-94,983	-72,890	-69,314	-78,034
Volkswagen	Trucks	66,586	101,487	91,064	78,727	91,469	99,663
Volvo	Cars	-23,033	-48,203	-49,395	-54,624	-57,555	-53,206
Volvo	Trucks	-8,464	7,081	8,903	5,401	3,256	6,332

Table 1.23 shows the difference in footprint distributions between the MY2015-based fleet projection and the MY2008-based fleet projection. The differences between MYs 2015 and 2008 are small, resulting from the manufacturers' projected product mix in those model years. MY2025 shows an increase in average car footprints. This is due to the significant decrease in subcompact cars forecast in the MY2015-based fleet projection. Truck footprints decrease slightly due to the increase in small SUVs. Because the total numbers of cars and trucks differs, production weighting can affect the average for the whole fleet as compared to the averages for cars and trucks. This can cause the result to appear counterintuitive when taking the difference of the averages.

Table 1.23 Difference in Footprint Distributions between MY2015-based and MY2008-based Fleet Projections

Model Year	Difference in Average Footprint of all Vehicles	Difference in Average Footprint Cars	Difference in Average Footprint Trucks
2015-2008	49.3- 48.9 = 0.4	46.1 – 45.4 = 0.7	53.7 - 54.0 = -0.3
2017	49.8 - 48.3 = 1.5	46.0 - 44.9 = 1.1	53.0 - 53.8 = -0.8
2018	49.7 - 48.1 = 1.6	46.1 - 44.9 = 1.2	53.0 - 53.7 = -0.7
2019	49.7 - 48.0 = 1.7	46.1 - 44.9 = 1.2	53.0 - 53.6 = -0.6
2020	49.5 - 48.0 = 1.5	46.1 - 44.9 = 1.2	53.0 - 53.7 = -0.7
2021	49.5 - 48.0 = 1.5	46.1 - 44.9 = 1.2	53.0 - 53.6 = -0.6
2022	49.5 - 47.9 = 1.6	46.1 - 44.9 = 1.2	53.0 - 53.6 = -0.6
2023	49.4 - 47.9 = 1.5	46.0 - 44.9 = 1.1	52.9 - 53.5 = -0.6
2024	49.3 - 47.7 = 1.6	46.0 - 44.9 = 1.1	52.9 - 53.4 = -0.5
2025	49.3 - 47.7 = 1.6	46.1 - 44.9 = 1.2	53.0 - 53.3 = -0.3

Table 1.24 shows the difference in the distribution of the number of engine cylinders between the MY2015-based fleet and the MY2008-based fleet. The MY2015 fleet includes fewer vehicles with 6- and 8-cylinder engines than the MY2008fleet. The presence of fewer 6- and 8-cylinder vehicles in the baseline fleet, along with vehicle mix changes, results in more 4-cylinder engines in trucks and cars by 2025.

Table 1.24 Differences in Percentages of 4, 6 and 8 Cylinder Engines by Model Year

	Trucks			Cars		
Model Year	4 Cylinders	6 Cylinders	8 Cylinders	4 Cylinders	6 Cylinders	8 Cylinders
2015-2008	18.1%	-5.2%	-12.8%	23.4%	-20.7%	-2.7%
2017	20.4%	-12.5%	-8.0%	19.3%	-17.1%	-2.1%
2018	21.7%	-14.3%	-7.4%	18.6%	-16.5%	-2.1%
2019	22.4%	-15.7%	-6.7%	18.7%	-16.5%	-2.1%
2020	22.6%	-15.9%	-6.7%	19.2%	-17.1%	-2.2%
2021	22.7%	-16.5%	-6.3%	18.9%	-17.0%	-1.9%
2022	22.6%	-16.5%	-6.0%	18.1%	-16.4%	-1.7%
2023	23.2%	-17.8%	-5.3%	18.3%	-16.6%	-1.8%
2024	23.0%	-18.3%	-4.7%	18.4%	-16.6%	-1.8%
2025	23.1%	-18.8%	-4.3%	18.3%	-16.5%	-1.8%

1.1.3.4 What Are the Differences in the Sales Volumes and Characteristics of the EPA MY2014-Based (Draft TAR) and the MY2015-Based Reference Fleets?

This section compares some of the differences between the MY2014-based reference fleet (used in the Draft TAR analysis) and the MY2015-based reference fleet used in the current analysis. As described earlier in this chapter, the MY2014-based reference fleet projection is based on several sources: MY2014 certification data, a long-range forecast provided by IHS-Polk Automotive, and the unforced AEO 2015. The MY2015-based reference fleet projection is based on MY2015 certification data, a long-range forecast provided by IHS-Polk Automotive (the same source used to create the 2016 fleet volumes), and the unforced AEO 2016. All tables in this section show the differences between the MY2014-based and MY2015-based fleets.

Table 1.25, Table 1.26, and Table 1.27 below list the sales volume differences between the two fleets, calculated by subtracting the MY2014-based fleet projection from the MY2015-based fleet projection. The sales in MY2015 were significantly higher (by 1,218,062 vehicles) than in MY2014. This suggests that automotive sales remain strong as advanced fuel-saving technologies have entered the market in response to the GHG/fuel economy standards, and that sales have increased even as the standards' stringency increased. In addition, this comparison demonstrates the need to use final sales year data to construct the baseline fleet, rather than mid-year fleet projections. The mid-year data provided by vehicle manufacturers to NHTSA did not reflect the actual substantial increase in sales that was seen in MY2015.

For MY2015, there is a small increase in the number of compact and midsize autos, and all SUVs (except the largest). For MY2025, the differences between the two forecasts is very small when compared to the size of the overall market, with the largest change being for pickup trucks at -246,276, which is only 1.5 percent of the total market and 3 percent of the truck market.

Table 1.25 Vehicle Segment Volume Differences

Reference Class Segment	Actual Sales Volume	Difference in Projected Sales Volume (2015-2014)				
	2015-2014	2021	2022	2023	2024	2025
SubCmpctAuto	-41,437	130,356	141,833	154,668	151,677	136,131
CompactAuto	19,228	-68,469	-51,745	-4,512	-81,261	-24,442
MidSizeAuto	366,984	105,689	134,839	186,828	136,170	156,879
LargeAuto	44,008	125,647	127,693	147,562	152,996	155,953
SmallPickup	-12,143	-15,227	-14,222	-16,067	-15,908	-16,123
LargePickup	-130,838	-235,294	-246,707	-233,482	-235,964	-246,276
SmallSuv	172,388	88,569	97,330	128,525	107,569	87,439
MidSizeSuv	656,145	141,260	127,151	121,146	141,228	106,402
LargeSuv	34,554	-20,285	-24,211	-16,511	-9,111	-20,463
ExtraLargeSuv	255,614	-51,336	-58,327	-52,516	-51,981	-55,367
MiniVan	-54,352	-59,725	-61,542	-63,043	-56,681	-78,215
CargoVan	-47,737	-57,663	-53,690	-58,918	-60,858	-63,169

Table 1.26 Differences in Actual and Projected Sales Volumes between MY2015 and MY2014 fleets

C/T Type	Difference in Actual Sales Volume	Difference in Projected Sales Volume				
	2015 - 2014	2021	2022	2023	2024	2025
Cars	391,150	526	78,901	208,341	173,114	117,786
Trucks	826,913	-30,693	-72,677	-36,652	-78,788	-111,998
Cars and Trucks	1,218,062	-30,167	6,225	171,689	94,326	5,788

Table 1.27 below contains the differences in sales volumes by manufacturer and C/T type between the 2014 MY based fleet and the 2015 MY based fleet. The manufacturers with the next largest increases in sales in 2015 MY (from 2014) are FCA cars, GM trucks, Honda cars, Hyundai/Kia cars, Nissan cars and trucks, and Toyota cars and trucks. The manufacturers with a net decrease in sales in 2015 (from 2014) are Aston Martin, Ford, JLR, Mazda, and Mercedes. The differences in forecasted volumes are relatively small.

Table 1.27 Differences in Sales Volumes by Manufacturer and Car/Truck Type between MY2014-based and MY2015-based fleets

Manufacturers	Segment Type	2015-2014 Difference in Sales	2021 Difference in Volume	2022 Difference in Volume	2023 Difference in Volume	2024 Difference in Volume	2025 Difference in Volume
All	Both	1,218,062	-30,167	6,225	171,689	94,326	5,788
All	Cars	391,150	526	78,901	208,341	173,114	117,786
All	Trucks	826,913	-30,693	-72,677	-36,652	-78,788	-111,998
Aston Martin	Cars	-153	60	68	87	77	77
Aston Martin	Trucks	0	0	0	0	0	0
BMW	Cars	41,316	18,668	22,079	28,049	26,191	24,070
BMW	Trucks	5,197	5,411	4,499	4,283	3,766	3,294
FCA	Cars	121,310	-72,065	-68,327	-57,334	-60,510	-64,580
FCA	Trucks	-29,878	-174,041	-174,870	-175,572	-181,415	-195,077
Ferrari	Cars	344	744	4,257	5,543	5,914	6,455
Ferrari	Trucks	0	0	0	0	0	0
Ford	Cars	-370,128	-103,403	-93,708	-81,800	-83,955	-96,358
Ford	Trucks	-102,611	-102,958	-111,309	-103,414	-105,913	-106,382
GM	Cars	-225,259	-57,491	-47,791	-28,774	-34,774	-48,048
GM	Trucks	360,407	-66,520	-74,663	-68,675	-75,402	-80,294
Honda	Cars	151,973	25,092	34,239	47,588	44,120	38,803
Honda	Trucks	-20,964	110,081	104,487	107,609	101,567	97,991
Hyundai/Kia	Cars	210,858	19,337	30,167	42,398	36,275	31,198
Hyundai/Kia	Trucks	23,860	68,341	65,663	74,274	71,742	70,503
JLR	Cars	3,277	-1,229	-969	-575	-699	-750
JLR	Trucks	-798	-984	-1,062	-485	-998	-1,104
Lotus	Cars	-280	-234	-232	-231	-232	-233
Lotus	Trucks	0	0	0	0	0	0
Mazda	Cars	-10,233	-36,292	-35,287	-29,957	-30,241	-33,496
Mazda	Trucks	-33	21,875	21,890	23,075	21,806	21,674
McLaren	Cars	346	41	54	79	82	73
McLaren	Trucks	0	0	0	0	0	0
Mercedes	Cars	-46,227	-8,095	-5,958	-2,854	-4,509	-6,530
Mercedes	Trucks	31,415	18,217	16,872	16,834	15,879	15,534
Mitsubishi	Cars	31,143	679	1,261	2,177	2,052	1,675
Mitsubishi	Trucks	9,538	5,904	5,660	6,102	5,892	6,326
Nissan	Cars	280,397	52,328	58,513	75,317	69,960	67,479
Nissan	Trucks	91,944	20,248	18,265	15,072	10,560	9,668
Subaru	Cars	66,274	6,089	7,746	9,749	8,872	8,298
Subaru	Trucks	90,565	58,299	53,318	58,105	55,433	56,031
Tesla	Cars	6,531	3,911	4,609	6,549	6,124	5,957
Tesla	Trucks	0	0	0	0	0	0
Toyota	Cars	103,549	71,759	82,501	100,317	96,860	92,042
Toyota	Trucks	354,247	45,351	39,021	45,199	39,630	33,796
Volkswagen	Cars	22	76,717	81,615	87,411	87,343	86,996
Volkswagen	Trucks	4,803	-42,347	-43,073	-41,478	-43,598	-45,973
Volvo	Cars	26,090	3,911	4,065	4,601	4,165	4,657
Volvo	Trucks	9,221	2,431	2,625	2,419	2,263	2,013

Table 1.28 below shows the differences in engine technology penetration between MY2015 and MY2014. One of the larger differences is indicated by the increased use of turbochargers by Ferrari, Ford, Mercedes, Volkswagen, and Volvo. Many manufacturers are also changing the type of variable valve timing employed. Significant increases in use of direct injection is indicated for Ford, Honda, Hyundai/Kia, Subaru, and Volvo.

Table 1.28 Change (2015-2014) in Engine Technology Penetration

Manufacturers	Vehicle Type	Turbo Charged	Super Charged	Single Overhead Cam	Dual Over Head Cam	Over Head Cam	Variable Valve Timing Continuous Intake Only	Variable Valve Timing Discrete	Variable Valve Discrete Lift Only	Variable Valve Lift and Timing Discrete	Vehicles without Variable Valve Timing or Lift	Cylinder Deactivation	Direct Injection
All	Both	1%	0%	0%	0%	0%	0%	-3%	0%	2%	1%	0%	4%
All	Cars	0%	0%	2%	-2%	0%	0%	-5%	0%	5%	0%	0%	1%
All	Trucks	3%	0%	-2%	3%	-1%	-1%	0%	0%	-1%	2%	-1%	9%
Aston Martin	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Aston Martin	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
BMW	Cars	2%	0%	0%	0%	0%	0%	0%	0%	4%	-4%	0%	2%
BMW	Trucks	0%	0%	0%	0%	0%	0%	1%	0%	-7%	6%	0%	0%
FCA	Cars	-3%	1%	0%	2%	-2%	-2%	-29%	0%	31%	0%	-3%	0%
FCA	Trucks	1%	0%	1%	6%	-7%	-7%	1%	0%	5%	1%	-7%	0%
Ferrari	Cars	32%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ferrari	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Ford	Cars	5%	0%	0%	0%	0%	0%	-2%	0%	0%	2%	0%	-4%
Ford	Trucks	19%	0%	-7%	7%	0%	0%	-16%	0%	0%	16%	0%	19%
GM	Cars	-3%	0%	0%	0%	0%	0%	-5%	0%	6%	0%	0%	6%
GM	Trucks	2%	0%	0%	4%	-4%	-3%	4%	0%	0%	-1%	-2%	9%
Honda	Trucks	0%	0%	-1%	1%	0%	0%	0%	0%	0%	0%	2%	40%
Honda	Cars	0%	0%	10%	-10%	0%	0%	0%	0%	0%	0%	1%	17%
Hyundai/Kia	Trucks	-3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	21%
Hyundai/Kia	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%
JLR	Cars	7%	-3%	0%	0%	0%	0%	4%	0%	-4%	0%	0%	0%
JLR	Trucks	18%	-18%	0%	0%	0%	0%	38%	0%	-38%	0%	0%	0%
Lotus	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Lotus	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mazda	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	7%
Mazda	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	4%
McLaren	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
McLaren	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mercedes	Cars	33%	0%	0%	0%	0%	0%	1%	0%	0%	-1%	0%	3%
Mercedes	Trucks	7%	0%	0%	0%	0%	0%	9%	0%	0%	-9%	0%	0%
Mitsubishi	Cars	-3%	0%	-3%	4%	0%	0%	0%	0%	0%	0%	0%	0%
Mitsubishi	Trucks	0%	0%	0%	0%	0%	0%	29%	-6%	-23%	0%	0%	0%
Nissan	Cars	-1%	0%	0%	-2%	0%	0%	-1%	0%	0%	2%	0%	2%

Nissan	Trucks	0%	-2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	-1%
Subaru	Cars	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	14%
Subaru	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tesla	Cars	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tesla	Trucks	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Toyota	Cars	2%	0%	0%	0%	0%	0%	0%	0%	-1%	0%	0%	0%
Toyota	Trucks	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Volkswagen	Cars	10%	-2%	-1%	1%	0%	0%	0%	0%	4%	-4%	0%	7%
Volkswagen	Trucks	14%	3%	0%	0%	0%	0%	-3%	0%	4%	-2%	0%	0%
Volvo	Cars	21%	6%	0%	0%	0%	0%	0%	0%	0%	0%	0%	74%
Volvo	Trucks	44%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 1.29 shows the difference in footprint distributions between the MY2015-based fleet projection and the MY2014-based fleet projection. The differences between MYs 2015 and 2014 are small, and are primarily the result of differences in the manufacturers' product mix in those model years. The decrease in large pickup trucks and the increase in small and midsize SUVs causes the average truck footprint and the overall average footprint to decrease slightly. The difference between the MY2014-based and MY2015-based forecasts are small.

Table 1.29 2015 Projection - 2014 Projection Production Weighted Foot Print Mean Difference

Model Year	Difference in Average Footprint of all Vehicles	Difference in Average Footprint Cars	Difference in Average Footprint Trucks
2015-2014	49.3 - 49.7= -0.5	46.1 - 46.0 = -0.1	53.7 - 55.0 = -1.3
2017	49.8 - 50.0 = -0.2	46.0 - 46.0 = 0	53.0 - 54.0 = -1
2018	49.7 - 50.1 = -0.3	46.1 - 46.1 = 0	53.0 - 54.0 = -1
2019	49.7 - 50.1 = -0.3	46.1 - 46.1 = 0	53.0 - 54.1 = -1.1
2020	49.5 - 50.0 = -0.5	46.1 - 46.1 = 0	53.0 - 54.0 = -1
2021	49.5 - 50.0 = -0.5	46.1 - 46.1 = 0	53.0 - 54.1 = -1.1
2022	49.5 - 50.0 = -0.5	46.1 - 46.1 = 0	53.0 - 54.1 = -1.1
2023	49.4 - 49.9 = -0.5	46.0 - 46.0 = 0	52.9 - 54.0 = -1.1
2024	49.3 - 49.9 = -0.6	46.0 - 46.0 = 0	52.9 - 54.0 = -1.1
2025	49.3 - 49.8 = -0.5	46.1 - 46.1 = 0	53.0 - 54.0 = -1

Table 1.30 shows the difference in distribution of number of engine cylinders between the MY2015-based fleet and the MY2014-based fleet. MY2015 includes fewer vehicles with 6- and 8-cylinder engines than MY2014. Fewer 6- and 8-cylinder vehicles in the baseline fleet, along with changes in product mix, results in greater representation of 4-cylinder engines in trucks and cars by 2025.

Table 1.30 Differences in Percentages of 4, 6 and 8 Cylinder Engines by Model Year

	Trucks			Cars		
Model Year	4 Cylinders	6 Cylinders	8 Cylinders	4 Cylinders	6 Cylinders	8 Cylinders
2015-2014	4.2%	-0.1%	-4.2%	3.0%	-2.9%	-0.1%
2017	4.8%	-0.7%	-4.2%	2.5%	-2.6%	0.1%
2018	4.8%	-0.5%	-4.3%	2.4%	-2.5%	0.1%
2019	5.0%	-0.7%	-4.3%	2.4%	-2.5%	0.1%
2020	4.9%	-0.8%	-4.1%	2.4%	-2.6%	0.2%
2021	5.0%	-0.7%	-4.3%	2.4%	-2.6%	0.2%
2022	5.1%	-0.9%	-4.2%	2.4%	-2.6%	0.2%
2023	5.2%	-1.0%	-4.2%	2.3%	-2.6%	0.2%
2024	5.2%	-1.0%	-4.2%	2.3%	-2.5%	0.2%
2025	5.1%	-0.9%	-4.2%	2.2%	-2.5%	0.2%

1.2 The OMEGA Fleet

The prior section presented the development of the baseline fleet and how future sales were estimated. For OMEGA, we do not apply the baseline fleet as presented above in its "raw" form for a number of reasons:

1) It includes small-volume manufacturers, which we exclude from this analysis since they are eligible to apply for unique standards.
2) Despite the need to generate future sales projections for modeling purposes, of perhaps greater importance to OMEGA is the technology characterization of the baseline fleet. That is, OMEGA needs "know" the level of technology on baseline vehicles so that it can properly track costs and effectiveness improvements going forward.
3) It focuses on consumer metrics for vehicle classification (e.g., small car, large car, SUV) rather than modeling metrics (e.g., road loads, power-to-weight ratios).
4) It does not include the ZEV program and the fleet of battery electric vehicles (BEVs) and plug-in electric vehicles (PHEVs) that are projected to be part of the nationwide fleet in the time frame of the analysis (MYs 2021 through 2025).

As a result, the baseline fleet as presented above undergoes a transition to put that fleet into a form and of proper content that it can be processed by OMEGA. Removing small-volume manufacturers from the baseline fleet is easily done as the first step by simply removing Aston Martin, Ferrari, Lotus and McLaren. The result is a slightly smaller fleet of remaining vehicles. The technology "walk" from what might be termed "real-world space" to "OMEGA space" is simply a process of coding specific technologies in the baseline fleet into the technology codes understood by OMEGA. To properly track costs, OMEGA must, for example, understand that a vehicle has a V8 rather than an I4 engine, since the two engines have very different cost metrics for certain additional technologies (for example, engine friction reduction) for which costs are based on the number of cylinders. Determining the road load and power-to-weight ratio metrics is also important for modeling, and is described in more detail in Chapter 2 of this TSD.

For the Proposed Determination analysis, converting the baseline presented in Chapter 1.1 into a ZEV program-compliant "OMEGA baseline" was performed in largely the same way as for the Draft TAR analysis. One notable difference is that, in the Draft TAR, EPA built ZEV program vehicles on the same platforms as the ICE vehicle from which the sales were taken. In this analysis, we have built those ZEV program vehicles on unique platforms. The result is a far greater number of platforms in this analysis, but this also allows us to essentially leave those existing ZEV program vehicles, and all BEV/PHEV vehicles in our analysis, alone. They simply pass through OMEGA untouched and unimproved. Their emissions, both tailpipe and upstream, are considered by OMEGA in determining a path toward compliance, but those vehicles are not considered for improvement since most already perform considerably better than their respective footprint-based targets.

1.2.1 Incorporation of the California Zero Emissions Vehicle (ZEV) Program into the OMEGA Reference Fleet

1.2.1.1 The ZEV Regulation in OMEGA

In its analysis for this Proposed Determination, EPA has considered sales of electrified vehicles as projected to be needed to meet state Zero Emission Vehicle (ZEV) requirements. Because these ZEVs are already required by separate regulations in California and nine other states, these vehicles are built into the OMEGA reference fleet. This approach reasonably avoids attributing costs to the federal GHG program which necessarily occur due to another existing requirement, and assures that those costs are not double counted. Note that this reflects a change from the 2012 FRM, where EPA did not account for compliance with the ZEV regulations in the reference case fleet for the 2017-2025 standards. However, this was because CARB was simultaneously substantially revising the ZEV regulation in early 2012 just prior to the release of the 2012 FRM, and EPA had not yet acted upon California's waiver request for the ZEV program. The approach described here is consistent with the approach EPA took in the Draft TAR.

Public comments on the Draft TAR included some comments related to our inclusion of ZEV program vehicles in the reference case. Specifically, the Alliance of Automobile Manufacturers and others commented that including compliance with the ZEV program as part of our reference fleet analysis was unfairly counting their benefits without estimating their costs.[I] This comment is mistaken. The presence of ZEV program vehicles in our analysis is done both in the reference and control cases. As such, costs associated with those vehicles and any benefits derived by them cancel out in calculating net benefits. EPA's methodology is also consistent with OMB Circular A-4, which states that in developing a baseline for purposes of analyzing the potential effects of a proposed rule,"[t]his baseline should be the best assessment of the way the world would look absent the proposed action."[J]

[I] EPA-HQ-OAR-2015-0287-0928 at Section 4.1.2.1.

[J] Office of Management and Budget Circular No. A-4, "Regulatory Analysis," at page 15, available at https://www.whitehouse.gov/omb/memoranda_m03-21.

Other commenters, including NGOs such as the Environmental Defense Fund and the Union of Concerned Scientists, believe that EPA correctly accounted for the ZEV program by including California's ZEV vehicles in its reference fleet, as this approach ensures that the costs of the ZEV program, which are not imposed by the 2022-2025 standards but rather by state law are not included as costs of the national rule. EPA agrees. The California ZEV program is an existing state requirement that has been adopted by California, as well as by several other states. Therefore, EPA included vehicles that are needed to comply with the ZEV program as part of our reference fleet in assessing the MY2022-2025 GHG standards. Thus, as explained above, the Draft TAR did not include an assessment of the benefits or the costs of the ZEV program in the assessment of 2022-2025 National Program standards. However, any ZEV vehicles sold in California and other states will help a manufacturer in meeting the EPA GHG standards. While the fleet-average GHG emissions standards establish minimum standards, they do not limit the ability of manufacturers to achieve further reductions, and any manufacturer that does will generate credits that can be used or sold. ZEVs sold in California and other states will help a manufacturer to meet (or exceed) the EPA GHG standards.

The conclusions presented in this analysis are meant to be one example representation of how the ZEV program requirements could be fulfilled; it is in no way meant to reflect the exact way in which any given manufacturer would actually comply with the ZEV program. Rather, it is meant as an illustration to reflect the potential number and penetration of ZEVs across the national fleet as part of the reference case. To accomplish this, the baseline fleet with future sales projections had to be adjusted to account for the projected ZEV sales. Those sales adjustments are described in detail below (see 1.2.1.2). The analysis fleets used in OMEGA and in EPA's benefit cost analysis for the AEO reference fuel price case are shown in Table 1.31 through Table 1.34, with additional breakdowns of these sales shares shown in Table 1.35.

Note that, in Table 1.31 through Table 1.34, EPA shows "Baseline" BEV and PHEV sales and "Additional ZEV Program" BEV and PHEV sales. The "baseline" sales are sales projected in EPA's MY2015-based baseline fleet. In other words, these vehicles are part of the future fleet described in Chapter 1.1. The "additional ZEV program" sales are BEV and PHEV sales above and beyond those projected in Chapter 1.1. The "additional ZEV program" sales were taken from the ICE-only sales that were projected in Chapter 1.1. We have not increased the size of the fleet, but have "converted" some ICE-only vehicles to BEVs and PHEVs to meet the projected sales required by the ZEV program in California and nine other states. We describe the process of doing this in the text following the tables. Importantly, the costs of "converting" the "additional ZEV program" sales are attributable to the ZEV program and, therefore, those costs are not considered in the EPA analysis. Similarly, any benefits from those vehicles are not considered explicitly in the EPA analysis. However, there is an implicit benefit that is considered. Since the ZEV program vehicles are part of the analysis fleet, they reduce slightly the GHG compliance burden (i.e., the fleet average GHG standards) for any manufacturer required to meet the ZEV program because the additional ZEVs, when averaged with other vehicles, lower that manufacturer's fleet average GHG emissions.[K] By starting with a lower

[K] Importantly, we have modeled MY2025 electricity consumption considering the upstream emissions. As a result, BEV and PHEV miles driven using full electric power are not considered zero. Because of this, the impact of the ZEV program vehicles is less in this analysis than it was in the Draft TAR since that analysis considered upstream emissions to be zero.

GHG-emitting baseline fleet, the compliance burden to get to the final standards is smaller but this necessarily also means that the calculated GHG benefits (the delta between the baseline and final standards) are also smaller. We model the fleet in this way because this is how ZEV program vehicles will be reflected in compliance with the national GHG standards.

Table 1.31 OMEGA MY2021 Car Fleet using the AEO 2016 Reference Fuel Price Case

	ICE-only Car Sales	Baseline BEV Sales	Baseline PHEV Sales	Additional ZEV Program BEV Sales	Additional ZEV program PHEV Sales	Total Car Sales
BMW	296,220	4,347	17,082	0	0	317,648
FCA	523,734	5,704	0	1,172	4,990	535,600
Ford	810,252	1,212	9,491	5,220	5,434	831,609
GM	1,118,223	1,688	28,544	5,889	0	1,154,344
Honda	800,481	0	0	7,472	11,705	819,658
Hyundai/Kia	1,110,746	589	0	6,700	11,118	1,129,153
JLR	22,382	0	0	214	336	22,932
Mazda	208,312	0	0	1,719	2,693	212,725
Mercedes	210,362	3,167	50	961	3,968	218,508
Mitsubishi	47,071	0	0	275	430	47,775
Nissan	785,250	25,188	0	34	9,732	820,204
Subaru	137,854	0	0	1,220	1,912	140,987
Tesla	0	90,547	0	0	0	90,547
Toyota	1,172,623	0	4,695	11,415	15,111	1,203,844
Volkswagen	526,653	2,737	1,343	3,026	7,761	541,520
Volvo	43,480	0	0	406	636	44,523
Fleet	7,813,644	135,179	61,204	45,723	75,827	8,131,578

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 1.32 OMEGA MY2021 Truck Fleet using the AEO 2016 Reference Fuel Price Case

	ICE-only Car Sales	Baseline BEV Sales	Baseline PHEV Sales	Additional ZEV Program BEV Sales	Additional ZEV program PHEV Sales	Total Car Sales
BMW	115,780	0	0	0	0	115,780
FCA	1,258,798	0	0	2,150	9,151	1,270,099
Ford	1,247,780	0	0	4,383	4,562	1,256,726
GM	1,254,629	0	0	3,401	0	1,258,030
Honda	841,687	0	0	7,856	12,308	861,851
Hyundai/Kia	224,154	0	0	1,352	2,244	227,750
JLR	100,048	0	0	957	1,500	102,505
Mazda	127,183	0	0	1,050	1,644	129,877
Mercedes	174,375	0	0	725	2,996	178,096
Mitsubishi	34,710	0	0	202	317	35,229
Nissan	573,978	0	0	21	5,941	579,939
Subaru	519,605	0	0	4,600	7,206	531,411
Tesla						
Toyota	1,055,084	0	0	7,243	9,588	1,071,915
Volkswagen	253,117	0	4,120	1,185	3,040	261,463
Volvo	47,705	0	0	446	698	48,849
Fleet	7,828,633	0	4,120	35,571	61,196	7,929,520

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 1.33 OMEGA MY2025 Car Fleet using the AEO 2016 Reference Fuel Price Case

	ICE-only Car Sales	Baseline BEV Sales	Baseline PHEV Sales	Additional ZEV Program BEV Sales	Additional ZEV program PHEV Sales	Total Car Sales
BMW	311,383	7,867	29,016	28	0	348,293
FCA	540,170	5,579	0	4,679	7,904	558,331
Ford	802,137	1,322	9,525	10,711	9,631	833,326
GM	1,189,943	2,186	31,131	12,938	3,484	1,239,682
Honda	848,485	0	0	16,107	18,926	883,518
Hyundai/Kia	1,153,285	535	0	14,543	17,515	1,185,878
JLR	23,499	0	0	458	538	24,494
Mazda	218,037	0	0	3,652	4,292	225,981
Mercedes	224,860	3,955	106	3,434	6,456	238,811
Mitsubishi	59,477	0	0	701	824	61,002
Nissan	846,189	26,490	0	6,734	16,017	895,430
Subaru	146,744	0	0	2,640	3,102	152,485
Tesla	0	109,459	0	0	0	109,459
Toyota	1,244,257	0	4,742	24,558	25,915	1,299,472
Volkswagen	573,109	3,049	1,509	8,708	12,811	599,186
Volvo	46,000	0	0	874	1,027	47,901
Fleet	8,227,574	160,441	76,029	110,766	128,441	8,703,251

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 1.34 OMEGA MY2025 Truck Fleet using the AEO 2016 Reference Fuel Price Case

	ICE-only Car Sales	Baseline BEV Sales	Baseline PHEV Sales	Additional ZEV Program BEV Sales	Additional ZEV program PHEV Sales	Total Car Sales
BMW	104,922	0	0	8	0	104,931
FCA	1,253,319	0	0	8,071	13,632	1,275,022
Ford	1,166,687	0	0	8,509	7,651	1,182,848
GM	1,191,481	0	0	6,613	1,780	1,199,874
Honda	802,944	0	0	15,243	17,910	836,097
Hyundai/Kia	221,511	0	0	2,794	3,365	227,669
JLR	90,516	0	0	1,762	2,071	94,350
Mazda	131,404	0	0	2,201	2,586	136,192
Mercedes	160,299	0	0	2,234	4,200	166,733
Mitsubishi	38,466	0	0	454	533	39,452
Nissan	539,914	0	0	3,481	8,280	551,676
Subaru	534,344	0	0	9,612	11,294	555,249
Tesla						
Toyota	1,003,343	0	0	13,661	14,416	1,031,420
Volkswagen	253,335	0	4,056	3,146	4,629	265,166
Volvo	46,980	0	0	893	1,049	48,921
Fleet	7,539,466	0	4,056	78,682	93,397	7,715,601

Note: The analysis fleet differs from the baseline fleet by removing small volume manufacturers (Aston Martin, Ferrari, McLaren, and Lotus) and by adjusting sales to account for projected ZEV sales.

Table 1.35 Breakdown of MY2025 Internal Combustion Engine, Electric and Plug-in Electric Vehicle Sales using the AEO 2016 Reference Fuel Price Case

	Car	Truck	Sum	Share
ICE-only	8,227,574	7,539,466	15,767,039	96.0%
Baseline BEV	160,441	0	160,441	1.0%
Baseline PHEV	76,029	4,056	80,085	0.5%
ZEV BEV	110,766	78,682	189,447	1.2%
ZEV PHEV	128,441	93,397	221,838	1.4%
Total ICE+BEV+PHEV	8,703,251	7,715,601	16,418,851	100.0%
Baseline BEV	160,441	0	160,441	24.6%
Baseline PHEV	76,029	4,056	80,085	12.3%
ZEV BEV	110,766	78,682	189,447	29.1%
ZEV PHEV	128,441	93,397	221,838	34.0%
Total BEV+PHEV	475,677	176,135	651,812	100.0%
ICE	8,227,574	7,539,466	15,767,039	96.0%
Baseline BEV+PHEV	236,470	4,056	240,527	1.5%
ZEV BEV+PHEV	239,207	172,079	411,285	2.5%
Total ICE+BEV+PHEV	8,703,251	7,715,601	16,418,851	100.0%
ICE	8,227,574	7,539,466	15,767,039	96.0%
Total BEV+PHEV	475,677	176,135	651,812	4.0%
Total ICE+BEV+PHEV	8,703,251	7,715,601	16,418,851	100.0%

The ZEV program sales are calculated based on the baseline fleet described in Chapter 1.1. From that fleet, we removed Aston Martin, Ferrari, McLaren and Lotus vehicles. That fleet includes some BEVs and PHEVs consistent with the sales in the MY2015 baseline fleet as projected forward to MYs 2021 and 2025. The additional ZEV program sales shown above in Table 1.31 through Table 1.34 were modeled as replacing ICE vehicles in the baseline fleet to maintain the same overall sales volume for each manufacturer's fleet. To "generate" the projected additional ZEV program vehicles, each model within a manufacturer's fleet was mapped into a vehicle type matching its characteristics and capability. For this analysis, it was assumed that only vehicle types classified as non-towing would be considered for conversion from an ICE to a ZEV to meet the ZEV program requirements. The 24 vehicle types considered for additional ZEV program sales include all of vehicle types not designated as large pickups. In other words, we now allow many more types of vehicles to electrify than we allowed in the Draft TAR or the 2012 FRM where we essentially limited BEV and PHEV electrification to passenger cars. Table 1.36 shows the 29 vehicle types being used in this analysis including the towing or non-towing designation and consideration as a “ZEV-source platform.” Rather than selecting which individual vehicle models or platforms would be the most likely sources, all ICE vehicles within the non-towing vehicle types in a manufacturer's fleet were considered as a source for additional ZEV program sales. Each manufacturer's additional ZEV program sales were then created by converting, on a platform-level sales weighted basis across all eligible vehicle types, the necessary number of ICE vehicles into the respective BEV and PHEV sales. By sales-weighting across all eligible vehicle types, the vehicle category and size (footprint) characteristics of each manufacturer’s fleet were kept consistent with the original baseline projections. The tables below are meant to provide clarity with a simple example of how this was done.[L]

Table 1.36 Vehicle Types Considered for Conversion to ZEV Program Vehicles

Vehicle Type	Description	Curb Weight Class	ALPHA Class	ZEV source?
1	I4 DOHC	1	LPW_LRL	Yes
2	I4 DOHC	1	MPW_LRL	Yes
3	I4 DOHC	2	MPW_LRL	Yes
4	I4 DOHC	2	LPW_HRL	Yes
5	I4 DOHC	3	MPW_LRL	Yes
6	I4 DOHC	3	LPW_HRL	Yes
7	I4 DOHC	4	LPW_HRL	Yes
8	I4 DOHC	6	Truck	No, Heavy-tow
9	V6 OHV	6	Truck	No, Heavy-tow
10	V6 SOHC	3	HPW	Yes
11	V6 SOHC	4	MPW_HRL	Yes
12	V6 DOHC	1	LPW_LRL	Yes
13	V6 DOHC	2	MPW_LRL	Yes
14	V6 DOHC	2	LPW_LRL	Yes
15	V6 DOHC	3	HPW	Yes
16	V6 DOHC	3	MPW_LRL	Yes
17	V6 DOHC	3	LPW_HRL	Yes
18	V6 DOHC	4	HPW	Yes
19	V6 DOHC	4	MPW_HRL	Yes
20	V6 DOHC	5	HPW	Yes
21	V6 DOHC	5	MPW_HRL	Yes
22	V6 DOHC	6	Truck	No, Heavy-tow
23	V8 OHV	5	HPW	Yes
24	V8 OHV	5	MPW_HRL	Yes
25	V8 OHV	6	Truck	No, Heavy-tow
26	V8 DOHC	4	HPW	Yes
27	V8 DOHC	5	HPW	Yes
28	V8 DOHC	5	MPW_HRL	Yes
29	V8 DOHC	6	Truck	No, Heavy-tow

Note: DOHC=dual overhead cam; SOHC=single overhead cam; OHV=overhead valve; Curb Weight Class is a percentile-based weight classification with 1 being the lightest and 6 being the heaviest vehicles; ALPHA class is described in Chapter 2.3 of this TSD and designates low/medium/high power-to-weight (L/M/HPW) and low/medium/high road load (L/M/HRL) or Truck which is used for large pickups like the Ford F150 and Chevy Silverado.

First, consider a simple manufacturer fleet consisting of seven vehicle models built on five platforms, which we have mapped into three vehicle types with total fleet sales of 600 vehicles, as shown in Table 1.37.

[L] The Excel spreadsheets used to generate the ZEV program fleet are in the docket and on our website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases. The filenames include the keyword "FleetsABC."

Table 1.37 Example Manufacturer Fleet from which ZEVs are to be Created

Platform index	Vehicle index	Model	Fuel	VehType	Baseline sales
100	1	A	G	1	100
100	2	B	G	1	100
101	3	C	G	2	75
101	4	D	G	2	75
102	5	E	G	1	100
103	6	F	G	2	50
104	7	G	G	29	100
Total					600

For this manufacturer, we will assume that the needed additional ZEV program sales are 50 BEVs and, for simplicity, no PHEVs. As noted above, vehicle types 8, 9, 22, 25 and 29 are not considered to be ZEV-source platforms. Thus, the 50 ZEV program vehicles cannot come from platform 104 since that is vehicle type 29. We determine the number of BEVs to create from each platform according to its sales weighting within ZEV-source platforms.[M] This is shown in Table 1.38. We also need to know how many vehicles within each vehicle model to convert to a ZEV program vehicle. This is shown in Table 1.39.

Table 1.38 Number of Additional ZEV Program Sales from each Platform

Platform index	VehType 1	VehType 2	Total	%in Platform	# of ZEV program sales
100	200		200	40%	20
101		150	150	30%	15
102	100		100	20%	10
103		50	50	10%	5
Total	300	200	500	100%	50

Table 1.39 Percentage of Additional ZEV Program Sales from Each Vehicle Model

Platform index	Model A	Model B	Model C	Model D	Model E	Model F	Total
100	50%	50%					100%
101			50%	50%			100%
102					100%		100%
103						100%	100%

With the details shown in Table 1.38 and Table 1.39, we can then convert ICE vehicles into ZEV program vehicles as shown in Table 1.40.

[M] The ZEV-source platforms are those platforms "mapped" into the 23 "ZEV platform" vehicle types presented in Table 1.36. The point of Table 1.36 is to make clear that we are creating ZEV program vehicles in only those types of vehicles that we believe to make the most sense. Those types of vehicles being passenger cars and sport and cross-over utility vehicles that are not generally heavy-towing vehicles. The ZEV program vehicles are created only from within those vehicle types and, therefore, the creation of ZEV program vehicles is done using sales-weighting within those vehicle types rather than within all vehicles.

Table 1.40 Example Manufacturer's OMEGA Fleet including ZEV Program Sales

Platform index	Vehicle index	Model	Fuel	VehType	Baseline Sales	OMEGA fleet with ZEV program sales
100	1	A	G	1	100	90
100	2	B	G	1	100	90
101	3	C	G	2	75	68
101	4	D	G	2	75	68
102	5	E	G	1	100	90
103	6	F	G	2	50	45
104	7	G	G	29	100	100
105	8	ZEV	E	1	0	20
106	9	ZEV	E	1	0	15
107	10	ZEV	E	2	0	10
108	11	ZEV	E	2	0	5
Total sales G					600	550
Total sales E					0	50
Total sales					600	600

As noted above, we then created each manufacturer's ZEV program fleet by converting, on a platform-level sales weighted basis, the necessary number of ICE vehicles into the respective BEV and PHEV sales. EPA staff considered an alternate approach to look instead at which specific platforms, or even vehicle models, were the best candidates for conversion to BEV/PHEV. However, that approach was rejected because there is no industry consensus on which characteristics make a vehicle the best candidate for conversion. Is it the smallest cars, the lightest cars, those that already have a BEV or PHEV version, etc.? Any attempt at determining the "best" candidates for conversion might be seen as "cherry picking" in order to provide a certain result. Some might see us as choosing all of the smallest vehicles, thereby leaving all of the larger, perhaps "dirtier" vehicles as ICE vehicles needing costly improvements to comply with the future standards. Others might see us as choosing all of the largest vehicles, thereby leaving all of the smaller, perhaps "cleaner" vehicles as ICE vehicles needing less costly improvements to comply with future standards. Further, there is no clear trend as to which vehicles or platforms manufacturers are currently using for BEV or PHEV platforms. Current and publicly-announced near term models span platforms from subcompact cars to large cars, large SUVs to minivans, and use of shared or dedicated platforms. Our final decision was to choose equally (by sales weighting) from each ZEV source platform such that there would be no net impact on the sales weighted footprint of remaining ICE vehicles needing technology to comply.

1.2.1.2 The ZEV Program Requirements

The preceding discussion describes how we determined which vehicles would be converted from ICE technology to BEV/PHEV. Here we discuss the assumptions regarding the characteristics of the ZEVs used in the analysis and how compliance (total sales) with the ZEV mandate was modeled.

1.2.1.2.1 Overview

California requires the largest vehicle manufacturers to manufacture ZEV credit producing vehicles to comply with the increasing number of ZEV credits required through 2025.[7] The ZEV credits can be generated by producing battery electric vehicles, fuel cell electric vehicles, and certain plug-in hybrid vehicles. In addition to the requirements applying in California (CA), several other states have used section 177 (S177) of the federal Clean Air Act to adopt the California ZEV requirements (referred to as S177 ZEV States).[8] These states, when combined with CA, account for nearly 30 percent of all new light-duty vehicles sold in the United States.

Under the ZEV regulation, manufacturers are required to generate ZEV credits to fulfill an annual obligation based on their cumulative vehicle sales as summarized in Table 1-40. Requirements are satisfied by producing vehicles that generate credit which, for MY2018 and beyond, means a combination of plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and fuel cell electric vehicles (FCEV). Each PHEV, BEV, and FCEV earns between 0.4 and 4 credits per vehicle depending on its electric range over a test cycle as specified in the CA ZEV regulation.[9] For example, a PHEV with a 10-mile electric range earns 0.4 credits and a BEV or FCEV with a 350-mile test range earns 4.0 credits.

To incorporate the ZEVs into the OMEGA fleet, the ZEV regulation credit requirements were converted to a vehicle sales requirement as follows:

1) Determine how many total ZEV credits each manufacturer will need in CA and the S177 ZEV states for each year being modeled in OMEGA (MY2021 and MY2025).
2) Develop a nominal BEV electric range (described in Table 4.33) and a nominal PHEV set of electric range characteristics (described in Table 4.34) that are projected to be representative of BEV and PHEV capability in the MY2021-2025 time frame. The range and characteristics are then used to determine how many ZEV credits each vehicle will generate. For simplification and alignment with existing OMEGA technology packages, FCEVs were not included in the compliance scenarios.
3) Calculate the incremental ZEV credits needed beyond those generated by any ZEVs already included in the OMEGA reference fleet projections and expected to be sold in CA and the S177 ZEV states.
4) Determine how many incremental BEVs and PHEVs each manufacturer will need to sell to satisfy their ZEV credit obligations for MY2021 and MY2025.

1.2.1.2.2 ZEV Credit Requirement

Each manufacturer's ZEV credit obligation is calculated by multiplying its projected total light duty vehicle sales in CA and S177 ZEV states by the ZEV credit percentage required (see Table 1.41 below). The total projected CA and S177 ZEV states sales volume for each manufacturer was calculated by multiplying the manufacturer-specific reference fleet national sales volumes in OMEGA by the CA and S177 ZEV states sales volume ratio (MY2014). For example, if manufacturer "A" is projected to sell 250,000 vehicles nationally in MY2021, and its CA and S177 ZEV state sales are 40 percent of its national sales, its projected MY2021 CA and S177 ZEV state sales would be 100,000 (250,000*40%). Although the regulation has flexibilities in the technologies a manufacturer may use to generate credits, there is a cap on the portion of the credits that can be satisfied with PHEVs as identified in Table 1.41. For example, if manufacturer "A" sells 100,000 vehicles in CA and the S177 ZEV states in 2021, it is required to generate 12,000 ZEV credits (100,000*12%) in 2021 and, of those 12,000 ZEV credits, only 4,000 (100,000*4%) can come from PHEVs. For the purpose of this analysis, manufacturers are projected to comply with the ZEV requirements by maximizing their ZEV credits earned using PHEVs and using BEVs to generate the remaining credits.

Table 1.41 ZEV Regulation Credit Requirements

	2018	2019	2020	2021	2022	2023	2024	2025
Total ZEV Credit Required	4.50%	7.00%	9.50%	12.00%	14.50%	17.00%	19.50%	22.00%
Max. Credits from PHEVs	2.50%	3.00%	3.50%	4.00%	4.50%	5.00%	5.50%	6.00%

1.2.1.2.3 Projected Representative PHEV and BEV Characteristics for MY2021-2025

The first step to calculate the number of ZEVs needed to meet the manufacturer's projected credit obligation is to determine the type of vehicles that will be used to comply with the regulation. The primary characteristic for determining ZEV credits per vehicle is the urban dynamometer driving schedule (UDDS) test cycle range for BEVs and the UDDS test cycle "equivalent all electric range" for PHEVs. ZEV credits are generated based on UDDS range, not label range, and a review of current certified BEVs indicates a UDDS range to label range correction factor of between 0.65 and 0.76. For this analysis, a value of 0.7 was used for all vehicles. Given that these would be future vehicles for which actual specifications are not yet known, assumptions were made regarding what future range(s) might be in the MY2021 and MY2025 time frame. Further simplifications of such projections were also necessary to fit within the existing model framework of OMEGA including baseline vehicles and technology packages. These simplifications include the use of a single nominal BEV range and a single nominal PHEV range for all manufacturers and all vehicle classes with characteristics projected to be representative of BEVs and PHEVs in the MY2021-2025 time frame. Given these constraints, this projection reflects a scenario for minimum compliance with the ZEV regulation using a representative nominal BEV and PHEV, but not a 'likely' scenario that might reflect a wide variety of different ranges of PHEV and BEV offerings across manufacturers, vehicle classes, and model years, or the inclusion of FCEVs, which have already begun to enter the market.

To develop the nominal BEV and PHEV electric range, EPA staff first looked at the relative impact of battery pack costs for a variety of battery costs (dollars per kilowatt-hour (kWh)). For this simplified analysis, vehicle energy consumption was assumed to be constant for all vehicle types; therefore, all-electric vehicle range and battery pack size increase proportionally. The relative costs to achieve longer range were then compared to the number of ZEV credits earned for the increased range. The qualitative results are shown in Figure 1.4. As the figure shows, building individual BEVs with a longer range directionally results in a lower cost per ZEV credit earned (i.e., satisfying the ZEV credit obligation with fewer long range BEVs is directionally more cost-effective than using a larger volume of shorter range BEVs). And, as Figure 1.4 illustrates, the relative impact is even larger at the lower battery costs projected for the 2022-2025 time frame. Accordingly, the nominal BEV and PHEV packages modeled longer range variants of both types of ZEVs rather than multiple variants of shorter and longer range vehicles. Note that the range of battery costs used in the figure (from $150/kWh to $300/kWh in the 2021-

2025 time frame) is generally consistent with the projections of the EPA battery costing analysis for PHEVs and BEVs as reported in Chapter 2.3.4.3.7 of this TSD. EPA's projected costs used in the 2012 FRM, the Draft TAR, and this analysis are supported elsewhere in the Draft TAR and this TSD, particularly in Chapter 5 of the Draft TAR where we evaluated the 2012 FRM and Draft TAR battery cost projections, and in Chapter 2 of this TSD where we discuss the battery cost projections used in this analysis.

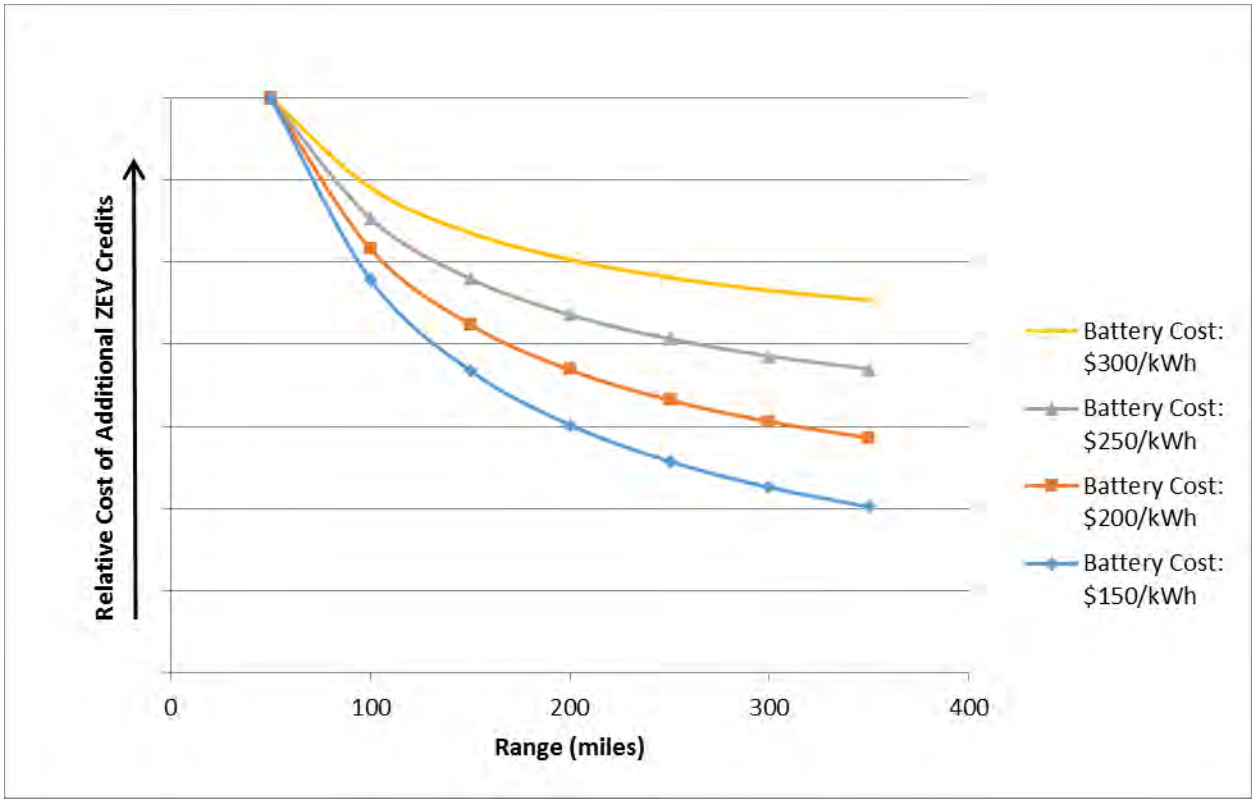


Figure 1.4 Relative Cost of ZEV Credits for Different Ranges and Battery Costs

The projected range for the nominal BEV and PHEV in the MY2021 to 2025 time frame was developed assuming a constant sales weighted average percent improvement from the current range. The MY2015 BEV sales-weighted label range is ~133 miles, as shown in Table 1.42 below; for MY2015 PHEVs, the sales-weighted label electric range is ~25 miles as shown in Table 1.43.

Table 1.42 Range Characteristics of BEVs for MY2015

Brand	Model	EPA Label All-electric Range (miles)
BMW	I3 BEV	81
BMW	I3 BEV	81
BMW	I3 REX	72
BMW	I3 REX	72
FCA	500e	87
Ford	Focus Electric FWD	76
GM	SPARK EV	82
Hyundai/Kia	Soul Electric	93
Mercedes	B-Class Electric Drive	87
Mercedes	smart fortwo elec. drive (conv.)	68
Mercedes	smart fortwo elec. drive (coupe)	68
Nissan	LEAF	84
Nissan	LEAF	84
Tesla	Model S	260
Tesla	Model S AWD	260
Volkswagen	e-Golf	83
Sales-Weighted Average Range (label Miles)		133

Table 1.43 Range Characteristics of PHEVs for MY2015

Brand	Model	EPA Label All-electric Range (miles)
Ford	C-Max Energi	20
Ford	Fusion Energi	20
Cadillac	ELR	37
Chevrolet	Volt	38
Toyota	Prius Plug-In	11
Sales-Weighted Average Range (label Miles)		25

For this analysis, the range for future vehicles was estimated to increase at a rate of 5 percent per year until the sales-weighted label range reaches 245 miles, which correlates to the maximum number of ZEV credits earned by any one vehicle. While manufacturers are not expected to actually redesign vehicles to increase the range every year nor to cap the range when they reach 245 miles, this rate of annual improvement is consistent with the improvements manufacturers have been making over more discrete intervals such as redesigns, refreshes, or other updates. For example, new or updated model introductions and announcements for the Ford Focus EV, VW e-Golf, Nissan Leaf, Tesla Model S, Tesla Model 3, Chevy Bolt EV, Chevy Volt PHEV, and BMW i3 have all included increased range compared to their predecessors. The 5 percent rate of growth is an estimated average of both longer and shorter range vehicles. It is not expected that BEVs with 200+ miles of range, such as some Tesla vehicles, will increase their range as quickly as shorter range vehicles such as the BMW i3. This is supported by the 2.5 percent per year increase observed in the Model S (85 to 90 kW-h) compared to the 9 percent per year increase seen by the GM Volt and the BMW i3. Additionally, while some OEMs may continue offering BEVs with lower ranges, these may be offset by longer range offerings such as hydrogen fuel cell electric vehicles (FCEVs) like those announced by Toyota and Honda, having ranges that well exceed 200 miles.

Given that the time period of interest is MY2021-2025 and that the ZEV requirements increase annually, a nominal range for the single BEV variant to be used for the model years of interest was determined by calculating the sales-weighted average for the years being evaluated. Table 1.44 combines the results from Table 1.42 for average electric range with the projected BEV sales for MY2021-2025 to calculate a sales-weighted average BEV for MYs 2021-2025. The sales-weighted average was calculated as 209 miles. Although this projection results in an estimated 209-mile range, a final range of 200 miles was chosen to provide for a potential slower-than-historical increase in range and to be consistent with an existing technology package in OMEGA (BEV200). EPA believes that a 200-mile label range is reasonable given recent announcements in this magnitude for the Tesla Model 3, GM Bolt EV, and an announced future Ford BEV which will all be available prior to MY2021.[N] For the model years being evaluated, all BEV200s are assumed to have a label range of 200 miles and a UDDS range of 286 miles which generates 3.36 ZEV credits per vehicle.

Table 1.44 Projected Sales Weighted BEV Range for MY2021-2025

Model year	BEV real-world range	BEV sales (% of whole fleet)	BEV sales (% of 2021-2025 cumulative BEV sales)
2021	187	2%	14%
2022	196	3%	17%
2023	206	3%	20%
2024	216	4%	23%
2025	227	4%	26%
Range Based on Sales Weighting MY2021-2025			209

The projected ranges for PHEVs in the MY2021-2025 time frame were calculated in a similar manner to the BEV ranges, with one minor difference. PHEVs generate credits based not only on electric range on the UDDS cycle, but also on the ability to drive all-electrically for at least 10 miles of the US06 supplemental FTP test cycle. PHEVs that can meet this US06 criterion earn an additional 0.2 credits per vehicle. While the reality is that motor, inverter, and battery pack sizing along with the powertrain architecture all play a role in determining whether a PHEV can meet this criterion, for this analysis, the ability to meet it was assumed to increase linearly for vehicles with electric range from 20 to 40 miles (i.e., 0 percent of PHEVs with 20-mile range, 50 percent of PHEVs with a 30-mile range, and 100 percent of PHEVs with 40-mile range can meet the US06 criterion). The analysis summarized in Table 1.45 shows that, for MYs 2021-2025, the sales-weighted average PHEV is projected to have a range of about 39 miles, which was rounded down to a final range of 40 miles to be consistent with an existing technology package (PHEV40) in OMEGA. A PHEV40 is assumed to be 100 percent US06 capable, so it generates 1.07 credits per vehicle after adjusting from a 40-mile label range to an equivalent UDDS range and including the additional credits for US06 capability. For perspective, the newly revised MY2016 GM Volt already exceeds this capability and other manufacturers are expected to further increase their range and capability over the next 5 to 9 years.

[N] More examples supporting the rationale for BEV200 and discussion of public comment on this topic can be found in Chapters 2.2.4.4.5 and 2.3.4.3.5 of this TSD.

Table 1.45 Projected Sales Weighted PHEV Range for MY2021-2025

Model year	BEV real-world range	PHEV sales (% of whole fleet)	PHEV sales (% of 2021-2025 cumulative PHEV sales)
2021	35	4%	17%
2022	37	4%	19%
2023	39	5%	20%
2024	41	5%	21%
2025	43	5%	23%
Range Based on Sales Weighting MY2021-2025			39

1.2.1.2.4 Calculation of Incremental ZEVs Needed for ZEV Program Compliance

Next, the number of ZEV credits generated from vehicles already included in the projected reference fleet was subtracted from the total credit obligation. Given that the projected reference fleet only included national sales numbers for ZEVs, those numbers were first scaled to California and S177 ZEV state sales using the current (average of MY2014 and MY2015) manufacturer-specific percentage of national ZEV sales in California and the S177 ZEV states. For this analysis, all manufacturers are projected to generate ZEV credits using the nominal BEV and PHEV all-electric ranges calculated above, and each manufacturer is projected to fulfill their credit requirements without exercising any of the various additional flexibilities included in the ZEV regulation. These earned credits were then subtracted from each manufacturer's credit obligation to calculate the remaining incremental credits needed. For example, if a manufacturer's ZEV credit obligation for MY2021 is 12,000 credits, and the original baseline projected 1000 BEV sales in California and the S177 ZEV states, its incremental obligation is 8,640 ZEV credits (12,000 credits -1000 vehicles*3.36 credits/vehicle).

Finally, the incremental credits needed were translated to the number of additional PHEV and BEV sales for each manufacturer. For this analysis, it was assumed that each manufacturer would satisfy the maximum amount of ZEV credits allowed with PHEVs, and the remaining portion with BEVs. Both the ZEVs in the original reference fleet and those incrementally added take this PHEV limitation into account. No ZEV credit trading and banking was included in this analysis; each manufacturer was assumed to meet its ZEV obligation in MY2021 and MY2025 with vehicles produced for those model years. For the projected sales volumes used in this analysis, the overall effect of the ZEV regulation is as shown in Table 1.31 through Table 1.34.

References

[1] EPA's Omega Model and input sheets are available at http://www.epa.gov/oms/climate/models.htm; Available in the docket (Docket EPA-HQ-OAR-2015-0827).
[2] U.S. Environmental Protection Agency (2012). "Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards." EPA-420-R-12-016, Chapter 10.
[3] The baseline Excel file ("2015-2025 Production Summary and Data with Definitions") is available in the docket (Docket EPA-HQ-OAR-2015-0827).
[4] Department of Energy, Energy Information Administration, Annual Energy Outlook (AEO) *Available at* http://www.eia.gov/forecasts/aeo/tables_ref.cfm (last accessed June. 15, 2016). The Department of Energy's Energy Information Administration is a principal agency of the United States Federal Statistical System responsible for collecting, analyzing, and disseminating energy information to promote sound policymaking, efficient markets, and public understanding of energy and its interaction with the economy and the environment. The Energy Information Administration's reports are the standard source, used government-wide, for such information and analysis.
[5] EIA special projections Excel file ("EPA_AEO2016_SPECIAL 2021_Cases") is available in the docket (Docket EPA-HQ-OAR-2015-0827).
[6] The baseline Excel file ("2014-2025 Production Summary and Data with Definitions") is available in the docket (Docket EPA-HQ-OAR-2015-0827).
[7] Title 13, California Code of Regulations, Section 1962.2 "Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles."
[8] Section 177 ZEV states: Connecticut, Maine, Maryland, Massachusetts, New York, New Jersey, Oregon, Rhode Island, and Vermont.
[9] Title 13, California Code of Regulations, Section 1962.2 "Zero-Emission Vehicle Standards for 2018 and Subsequent Model Year Passenger Cars, Light-Duty Trucks, and Medium-Duty Vehicles."

Table of Contents

Table of Figures

Table of Tables

Chapter 2: Technology Costs, Effectiveness, and Lead Time Assessment

2.1 Overview

Technology assessment was a critical element of the development of the 2017-2025 GHG standards in the 2012 final rulemaking (FRM). The standards were ultimately guided by a detailed assessment of GHG-reducing technologies that were available as of the 2012 calendar year time frame. The assessment included technologies that were currently in production at the time, or pending near term release, as well as consideration of further developments in technologies where there was reliable evidence that those technologies could be feasibly deployed by 2025.

As the first step in the MTE process, the 2016 Draft TAR summarized the current state of technology through the mid-2016 time frame, including technology developments since the FRM and the outlook for future developments through MY2025. The Draft TAR found that the fleet penetration of many of the GHG-reducing technologies identified in the FRM has proceeded steadily, accompanied by new technologies not anticipated at the time. Technology assumptions for cost, effectiveness, and availability were then revised and incorporated into the Draft TAR GHG Assessment, a substantial and comprehensive update to the assessment performed for the 2012 FRM.

This Chapter 2 of the Proposed Determination Technical Support Document (TSD) provides EPA's updated assessment of the current state of technology and likely future developments through MY2025. A description of the technical work that has been done to inform the Draft TAR and the Proposed Determination analysis is also included in this chapter, along with a summary of the assumptions and inputs used to characterize technologies in the analysis. In the cases where public comments received on the Draft TAR or updated information gathered since the Draft TAR have contributed additional insight on the current state of technology or on assumptions for technology cost and effectiveness, this information is incorporated into the discussion. The results of EPA's Proposed Determination analysis are discussed in Section IV of the Proposed Determination document.

In researching the Draft TAR, the agencies (EPA, NHTSA, and CARB) relied on many sources to evaluate the state of technology, including vehicle certifications, vehicle simulation modeling, reviews of technical papers and conference proceedings, agency meetings with vehicle manufacturers and suppliers, and the 2015 NAS report. This collaborative effort produced an extensive catalog of information on fuel-saving and GHG-reducing technologies that built upon the 2012 FRM assessment. In developing the assessment for this Proposed Determination, EPA has built further upon the body of information relied on for the Draft TAR assessment, by continuing our in-house vehicle benchmarking testing program, enhancing and refining our models, assessing the latest available data and literature, and considering public comments received on the Draft TAR.

It is clear that the automotive industry is innovating and bringing new technology to market at a brisk pace. Many of the technologies that figured prominently in the analysis performed for the 2012 FRM, such as gasoline direct injection, turbocharging and downsizing, and higher-efficiency transmissions, have seen continued market penetration, and continued to have an important role in the Draft TAR analysis. Even some well-established technologies had advanced enough to require a re-evaluation of cost, effectiveness, and implementation for the Draft TAR. For example, the ongoing improvements in transmissions with higher ratio spreads and gear count, and the application of light-weight materials that had previously been applied only to high-performance and luxury vehicles, were beginning to appear in mass-market vehicles. While the cost, effectiveness,[A] and feasibility of implementation of individual technologies projected in the Draft TAR were generally consistent with the compliance pathways projected in the 2012 FRM, some developments did not unfold as predicted. The Draft TAR found that several new technology applications not considered in the FRM analysis, or which had been predicted to have very low market penetration, had continued to evolve and deserved a reassessment. For example, Atkinson Cycle engines have now been applied to non-hybrids successfully, and continuously variable transmissions (CVTs) have entered the market more widely than originally expected in applications that have been well-received by consumers and expert reviewers. Another example is 48-volt mild hybridization, which by some accounts is gathering momentum rapidly, offering significant efficiency benefits with lower complexity and system cost compared to the higher voltage mild hybrid systems examined in the FRM analysis. The Draft TAR built upon the FRM technology assessment by recognizing these technology developments and incorporating many of them into the Draft TAR technology assessment.

Although some comments received on the Draft TAR were critical of EPA's assessment of the effectiveness of some technologies, as a whole, EPA believes that the Draft TAR was broadly accurate in its characterization of technology effectiveness. Through our consideration of public comments on the Draft TAR, as well as continued analysis of sources such as current vehicle certifications, continued benchmarking activities, literature reviews and modeling, it is our assessment that the effectiveness values developed for the Draft TAR are largely fair and accurate representations of benefits achievable by manufacturers within the time frame of the rule. This is not to imply that every manufacturer that has added a technology has achieved the effectiveness estimated in the Draft TAR. Some applications of technology are in their first or second design iteration, and we expect that successive iterations will improve their effectiveness. One example is the emerging use of integrated and cooled exhaust manifolds and the resulting improved effectiveness from turbo-charged downsized engines. Some manufacturers that have adopted technology have used some of the benefit to improve other vehicle attributes, rather than solely to improve fuel economy. For example, the efficiencies gained can often be used to promote other attributes such as acceleration performance, cargo capacity, towing capability, and/or vehicle size and mass while holding fuel economy relatively constant. Vehicle manufacturers have adopted many examples of technologies that perform very well, such as the Mazda SKYACTIV-G® engine and the ZF 8-speed transmission, and when these technologies are combined with the sole intent of improving vehicle efficiency, our analysis continues to show that significant improvements from the baseline fleets are broadly achievable using conventional powertrains.

This Chapter 2 provides a complete description of EPA's assessment of the status, cost, effectiveness, and application of the technologies that we considered in this analysis. We have included a brief review of the technology assessment conducted for the Draft TAR, as well as a

---

[A] The term 'effectiveness' is used throughout this Chapter to refer both to a reduction in tailpipe CO_2 emissions and a reduction in fuel consumption. In cases where the two are not equivalent (e.g., when changing fuel type), separate values are presented.

summary of the updates that further inform the Proposed Determination assessment. Finally, we discuss how we synthesized all of the available information to derive our conclusions for cost, effectiveness, and application that informed the Proposed Determination technology assessment.

Like the technology assessment conducted for the Draft TAR, the Proposed Determination technology assessment includes a wide array of fundamental assumptions, modeling constructs, and general methodologies, as well as assumptions for cost and effectiveness of specific fuel-saving and GHG-reducing technologies. Key changes and updates EPA has implemented for this Proposed Determination assessment include:

- An updated baseline fleet, based on MY2015 GHG compliance data, the latest complete data set available
- Updated projections of future fuel prices and vehicle sales to AEO 2016, the latest available
- All monetized values are updated to 2015 dollars
- Better accounting for tire and aerodynamic improvements in the baseline fleet
- Updated accounting for light duty truck mass reduction in the baseline fleet
- Updated ZEV program sales using data from the California Air Resources Board
- Updated vehicle class definitions for modeling effectiveness to improve representativeness of power-to-weight and road load characteristics
- Expanded vehicle classification structure from 19 to 29 vehicle types to improve the resolution of cost-effectiveness estimates as applied in the OMEGA model
- Updated characterization and modeling of certain advanced engine technologies, including Atkinson cycle
- Updated effectiveness estimates for certain advanced transmission technologies
- Updated battery costs for plug-in vehicles, resulting from several battery modeling improvements such as an improved battery sizing method, updated data from electrified vehicles released or certified since the Draft TAR, and an updated accounting for energy consumption and road load technology improvements
- Added accounting in the compliance modeling for upstream emissions of plug-in vehicles phasing in from MYs 2022 to 2025
- Incorporated additional off-cycle technology options into OMEGA to better account for manufacturer's expected use of off-cycle credit opportunities
- Conducted additional sensitivity analyses to show the cost and technology penetration impacts of alternative technology pathways
- Updated our vehicle simulation model, ALPHA, to include the latest data on technology effectiveness from the EPA vehicle benchmarking testing program and other sources, across vehicle types
- Added quality assurance checks of technology effectiveness estimates into ALPHA and the lumped parameter model (LPM)

Complete descriptions of these changes, as well as discussion of public comments received on the Draft TAR and updated information contributing to the Proposed Determination assessment, can be found in the corresponding technology and methodology chapters of this TSD.

The remaining sections of this chapter provide detail on the state of development of specific fuel-saving and GHG-reducing technologies, and their estimated cost and effectiveness.

Section 2.2 of this chapter presents EPA's assessment of the current state of individual technologies and the advancements that have occurred since the 2012 FRM and up to the completion of the Draft TAR. EPA has reexamined every technology considered in the Draft TAR, as well as assessed some technologies that are currently commercially available but did not play a significant role in the Draft TAR analysis. We have also considered emerging technologies for which enough information has become known that they may be included in this Proposed Determination assessment. The categories of technologies discussed include engines, transmissions, electrification, aerodynamics, tires, mass reduction, and several other vehicle technologies. In addition, Chapter 2.2.9 provides an overview of the air conditioning efficiency and leakage credit provisions, a summary of the situation regarding low global warming potential (GWP) refrigerant, and discussion of key comments received on these topics. Chapter 2.2.10 provides a summary of the off-cycle credit program and an overview of how off-cycle credits have been used by manufacturers in their current compliance with the GHG program. Chapter 2.3.4.9 (Additional Off-cycle Credits and Costs) details how off-cycle credits have been considered in the Proposed Determination analysis. Key comments on the off-cycle credit provisions are addressed in Section B.3.4 of the Proposed Determination Appendix.

Section 2.3 of this chapter presents details of the approaches, assumptions, and technology inputs used in the Proposed Determination technology assessment.

The particular details of the assessment begin in Chapter 2.3.1 with a description of the fundamental assumptions for performance neutrality, fuels, methods for measurement of cost and effectiveness, and approach to vehicle classification, which together comprise the underpinnings of the technical analysis.

Chapter 2.3.2 focuses on the approach for determining technology costs, which includes the determination of both direct and indirect costs, as well as the application of cost reduction through manufacturer learning, and maintenance and repair costs. The methodologies used to develop technology costs remain largely unchanged from the Draft TAR. However, as was the case in the Draft TAR, technology cost inputs have again been reevaluated based on updated information and comments received on the Draft TAR.

Chapter 2.3.3 describes the approach for investigating technology effectiveness. Vehicle benchmarking is one of the foundations of EPA’s analysis of technology effectiveness. A description of testing and benchmarking conducted by EPA can be found in Chapter 2.3.3.1. Modeling of effectiveness across the vehicle fleet involves grouping vehicles into classifications, and the approach to classifying vehicles for this purpose is described in Chapter 2.3.3.2. These classifications and the data collected through benchmarking are used by EPA's full vehicle simulation model, known as ALPHA. The ALPHA model is described in Chapter 2.3.3.3. An outline of sources and methods for determining technology effectiveness is provided in Chapter 2.3.3.4. EPA's modeling methodology also includes use of a "lumped parameter model" (LPM), which models incremental effectiveness differences between vehicle technology packages. Updates to the LPM and its application in the Proposed Determination assessment are described in Chapter 2.3.3.5.

Chapter 2.3.4 describes the specific data and assumptions for individual technologies that are used in this Proposed Determination assessment. Informed by all of the information on the state of technologies described in Section 2.2, these inputs and assumptions for cost, effectiveness, and technology application ultimately led to the OMEGA model determination of the cost-minimizing compliance pathways that are outlined in Section IV of the Proposed Determination document and described in full detail in Section C of the Proposed Determination Appendix.

2.2 State of Technology and Advancements since the 2012 Final Rule

2.2.1 Individual Technologies and Key Developments

2.2.1.1 List of Technologies Considered

The key technologies considered in this Proposed Determination technology assessment are summarized below. Assumptions for cost, effectiveness, or application of some of these technologies have been updated for this Proposed Determination assessment, while others remain unchanged from the Draft TAR where EPA has determined that changes are not warranted. Full discussion of these technologies and any applicable updates is provided in the corresponding technology sections of this chapter.

A number of technologies that were considered in the 2012 FRM analysis underwent significant updates in the process of developing the Draft TAR assessment, which was a major update of the FRM assessment representing more than four years of active technology evolution and development throughout the automotive industry. Some of these most actively changing technologies were significantly updated for the Draft TAR analysis, and in some cases further updated for the Proposed Determination analysis. They include:

- HEV Atkinson cycle engines
- Non-HEV Atkinson cycle engines
- Turbocharging and downsizing
- Miller Cycle Engine
- Direct Injection Miller Cycle Engine
- Turbocharger improvements
- Cylinder deactivation
- Variable geometry valvetrain systems (VVT, DVVL, CVVL)
- Continuously variable transmissions (CVTs)
- Dual clutch transmissions (DCTs)
- 48-volt mild hybrid electric vehicles (MHEVs)

Other technologies that were included in the FRM and the Draft TAR analysis, some of which also received updates to how they were represented in the Proposed Determination analysis, include:

- Stoichiometric gasoline direct injection
- Exhaust gas recirculation with boost
- Low-friction lubricants
- Second level of low-friction lubricants and engine friction reduction
- Reduction of engine friction losses
- Diesel engines
- Improved automatic transmission controls
- Increased gear-count automatic transmissions

- Shift optimization
- Manual 6-speed transmission
- High efficiency gearbox (automatic, DCT, CVT, or manual)
- Low-rolling-resistance tires
- Aerodynamic drag reduction
- Mass reduction
- Low-drag and zero drag brakes
- Secondary axle disconnect for four-wheel drive systems
- Electric power steering (EPS)
- Improved accessories (IACC)
- Low-leakage and higher-efficiency air conditioner systems
- Non-hybrid 12-volt stop-start
- High-voltage mild and strong hybrids (HEVs), including strong P2 and power split
- Plug-in hybrid electric vehicles (PHEVs)
- Battery electric vehicles (BEVs)

Each of these technologies are described in more detail in the following section. Full detail of the current development state of each technology can be found in the remaining sections of this chapter.

2.2.1.2 Descriptions of Technologies and Key Developments since the FRM

As described in the previous section, a number of technologies considered in the 2012 FRM analysis underwent significant updates in the process of developing the Draft TAR assessment. Some technologies that had not been considered in the 2012 FRM were added for the Draft TAR analysis, while others that had been included had developed differently than expected, and were updated accordingly.

This section provides capsule descriptions of the fuel-saving and GHG-reducing technologies considered in the Proposed Determination assessment, beginning with this subset of actively changing technologies that largely distinguished the Draft TAR assessment from the 2012 FRM assessment. It highlights some of the key considerations and updates that affected how each of these technologies were considered for the Draft TAR and, in many cases, further consideration and updates that were implemented for the Proposed Determination assessment. Other technologies that were considered in both the 2012 FRM and Draft TAR assessments, and which continue to be considered in the Proposed Determination assessment, are also outlined in this section.

This section is meant to provide only a brief outline of the technologies that EPA considered. For complete descriptions of the state of development of each technology, please refer to Chapters 2.2.2 through 2.2.10. Specific assumptions for cost and effectiveness for each technology as applied to the Proposed Determination assessment are discussed in Chapter 2.3.4.

HEV Atkinson cycle engines. These engines have a substantial increase in geometric compression ratio[B] (in the range of 12.5 - 14:1) and intake valve event timing to provide much later intake valve closing (LIVC). This lowers the trapped air charge, effectively lowering actual compression ratio to reduce knock-limited operation while maintaining the expansion ratio for improved efficiency. Although producing lower torque at low engine speeds for a given displacement, this engine has specific high efficiency operating points and is capable of significant CO_2 reductions when properly matched to a strong hybrid system. Electric motor/generators produce high torque at low speeds and are thus are capable of offsetting low engine speed torque deficiencies with Atkinson Cycle engines.

Non-HEV Atkinson cycle engines. For non-HEV applications, this technology often combines direct injection, a substantial increase in geometric compression ratio (in the range of 13-14:1), wide authority variable intake camshaft timing, variable exhaust camshaft timing, and an optimized combustion process to enable significant reductions in CO_2 compared to a standard direct injected engine. This engine is capable of changing the effective compression ratio by varying intake valve events enabling Otto and Atkinson operation. This multiple mode capability enables these engines to be applied in hybrid and non-hybrid applications. The ability to reduce pumping losses over a large area of operation may allow avoidance of the additional cost of higher gear count transmissions. The Mazda SKYACTIV-G engine is one example of this technology. The 2GR-FKS engine used in the MY2015-2017 Toyota Tacoma pickup truck is another example. The 2.0L "Nu" engine in the MY2017 Hyundai Elantra is another example of use of Atkinson Cycle in non-HEV application, although the "Nu" Atkinson engine uses PFI instead of GDI and has a slightly lower geometric CR than used by Mazda. The Toyota 1NR-FKE and 2NR-FKE Atkinson Cycle engines use both PFI and cEGR instead of GDI. In the FRM, the use of Atkinson Cycle engines was primarily considered in HEV applications. In the past few years, a new generation of naturally-aspirated SI Atkinson Cycle engines applicable to non-HEVs has been introduced into light-duty vehicle applications. The most prominent application of this technology is the Mazda SKYACTIV-G® system. It combines direct injection, an ability to operate over an Atkinson Cycle with increased expansion ratio, wide-authority intake camshaft timing, and an optimized combustion process. Other OEMs have intruded non-HEV Atkinson Cycle engines using PFI instead of GDI, in some cases combined with cooled, external EGR (cEGR). This type of engine operation is also not limited to naturally aspirated engines and when applied to boosted engines is referred to as "Miller Cycle," as described below. In addition to Mazda, other manufacturers using non-HEV application of Atkinson Cycle engines include Hyundai, Toyota, and FCA.

Turbocharging and downsizing. This approach increases the available airflow and specific power level, allowing a reduced engine size while maintaining performance. This reduces pumping losses at lighter loads in comparison to a larger engine. In the FRM, turbocharged,

[B] Geometric compression ratio is a ratio of the piston clearance volume + displacement swept volume to the displacement swept volume in a reciprocating piston engine. The actual effective compression ratio and expansion ratio must also take into account valve events governing the actual flows involved in the combustion process. Effective compression ratio and expansion ratios for typical Otto-cycle engines are nearly equivalent and governed by the chosen geometric compression ratio. Atkinson and Miller Cycle engines lower the trapped air or air-fuel charge volume during intake via either late intake valve closing or early intake valve closing to reduce effective compression ratio while simultaneously increasing effective expansion ratio. This is done by reducing the piston clearance volume and thus increasing the geometric compression ratio.

downsized engines were anticipated to be a prominent technology applied by vehicle manufacturers to improve vehicle powertrain efficiency. The penetration rate of turbo-downsized engines into the light-duty fleet has increased from 3 percent in 2008 to 16 percent in 2014.[1] The Draft TAR recognized that turbocharged, downsized engines are adopting head-integrated exhaust manifolds or separate, water-cooled exhaust manifolds. These systems also use separate coolant loops for the head/manifold and for the engine block. The changes allow faster warmup, improved temperature control of critical engine components, further engine downspeeding, and reduce the necessity for commanded enrichment for component protection. The net result is improved efficiency over the regulatory cycles and during real world driving. Engine downspeeding also has synergies with recently developed, high-gear-ratio spread transmissions that may result in further drive cycle efficiency improvements. In this Proposed Determination, consistent with the Draft TAR, EPA considered two levels of boosting, 18 bar brake mean effective pressure (BMEP) and 24 bar, as well as four levels of downsizing, from I4 to smaller I4 or I3, from V6 to I4, and from V8 to V6 and I4. 18 bar BMEP is applied with 33 percent downsizing and 24 bar BMEP is applied with 50 percent. To achieve the same level of torque when downsizing the displacement of an engine by 50 percent, approximately double the manifold absolute pressure (2 bar) is required.

Miller Cycle Engine. This technology combines direct injection, a significant increase in geometric compression ratio relative to other boosted engines, wide authority intake camshaft timing, and variable exhaust camshaft timing, and an optimized combustion process to enable significant reductions in CO_2 as compared to a standard direct injected engine. This is essentially Atkinson Cycle with the addition of a turbocharger boosting system. The addition of a turbocharger improves volumetric efficiency and broadens the areas of high-efficiency operation. The ability to reduce pumping losses over a large area of operation may allow avoidance of the additional cost of higher gear count transmissions. Examples include the Mazda SKYACTIV-G Turbo engine used in the MY2017 CX9; the VW EA211 evo 1.5L I4, EA888 3B 2.0L I4, and EA839 3.0L V6; the Toyota 8NR-FTS 1.2L I4 and 8AR-FTS 2.0L I4; the PSA 1.2L I3 PSA EB Puretech, and the Honda L15B7 1.5L I4.

Direct Injection Miller Cycle Engine. This new generation of turbocharged GDI engine combines direct injection, the ability to operate over a Miller Cycle (boosted Atkinson Cycle) with increased expansion ratio, wide-authority intake camshaft timing, and an optimized combustion process. Current manufacturers include VW, Mazda, Toyota, and PSA.

Turbocharger improvements. Newer turbochargers have been developed that reduce both turbine and compressor inertia allowing faster turbocharger spool-up. Improvements have been made to broaden the range of compressor operation before encountering surge and to improve compressor efficiency at high pressure ratios. The introduction of head-integrated exhaust manifolds or separate, water-cooled exhaust manifolds reduces exhaust turbine inlet temperatures under high-load conditions and improves exhaust temperature control. This allows the use of less expensive, lower temperature materials for the turbine housing and exhaust turbine. Reduced turbine inlet temperatures also allow the introduction of turbochargers with variable nozzle turbines into SI engine applications, similar to those used in light-duty diesel applications. Twin-scroll turbochargers are finding broad application in turbocharged, downsized GDI engines. Twin-scroll turbochargers improve turbocharger spool-up and improve torque output at lower engine speeds, allowing further engine downspeeding. Turbochargers with variable nozzle turbines (VNT) are now common in light-duty diesel applications and are under development for gasoline spark ignition engines, particularly those that use cooled EGR and head-integrated exhaust manifolds.

Cylinder deactivation. This technology deactivates the intake and exhaust valves and prevents fuel injection into some cylinders during light-load operation. The engine runs temporarily as though it were a smaller displacement engine with fewer cylinders which substantially reduces pumping losses. Cylinder deactivation applied to engines with less than six cylinders was not analyzed as part of the FRM. Further developments in NVH (noise, vibration, and harshness) abatement, including the use of dual-mass dampening systems, have resulted in the recent introduction of a 4-cylinder/2-cylinder engine into the European light-duty vehicle market. The development of rolling or dynamic cylinder deactivation systems allows a further degree of cylinder deactivation for odd-cylinder (e.g., 3-cylinder, 5-cylinder) inline engines than was possible with previous cylinder deactivation system designs. Both 3-cylinder/2-cylinder and 3-cylinder/1.5-cylinder (rolling deactivation) designs are at advanced stages of development.

Variable geometry valvetrain systems. This technology includes systems that vary valve timing and/or valve lift. *Variable valve timing* alters the timing or phase of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control residual gases. *Discrete variable valve lift* increases efficiency by optimizing air flow over a broader range of engine operation which reduces pumping losses, and is accomplished by controlled switching between two or more cam profiles. *Continuous variable valve lift* is an electromechanically controlled system in which cam period and phasing is changed as lift height is controlled. This yields a wide range of performance optimization and volumetric efficiency, including enabling the engine to be valve throttled. Variable geometry systems were anticipated in the FRM and Draft TAR to be important technologies for reducing engine pumping losses.

Continuously variable transmissions (CVTs). This transmission uses a belt or chain between two variable ratio pulleys, allowing a continuous (infinite) range of gear ratios and enabling the engine to operate in a more efficient operating range over a broad range of vehicle operating conditions. EPA did not assign a significant role to CVTs in the FRM analysis in part because of indications that some manufacturers had experienced consumer acceptance problems with CVTs, largely due to differences in shift feel compared to a conventional automatic transmission. Since the FRM, a new generation of CVTs has been introduced into the light-duty market by several OEMs. These new CVTs have significant improvements in shift feel as well as efficiency, and have achieved a wider ratio spread. CVTs have become increasingly common in manufacturers' product lines today.

Dual clutch transmissions (DCTs). This transmission is similar to a manual transmission, but the vehicle controls shifting and launch functions. A dual-clutch automated shift manual transmission uses separate clutches for even-numbered and odd-numbered gears, so the next expected gear is pre-selected, which allows for faster, smoother shifting. Early DCTs, mostly in non-performance vehicles, were accepted in Europe but were not widely accepted in the North American market, in part because launch and shift characteristics differed from conventional automatic transmissions. However, strategies have been developed to improve overall DCT operational characteristics. DCTs occur in variations called wet clutch, dry clutch, and "damp clutch." The damp clutch DCT combines the durability and driveability of a wet clutch with the efficiency of a dry clutch DCT. The combination of a DCT with a torque converter can greatly improve operational characteristics and eliminates the need for complex crankshaft dampers and other NVH technologies. The elimination of these NVH technologies approximately offsets the additional cost of the torque converter. DCTs also can be integrated into P2-architecture HEVs as well as 48-volt P2 hybrid drive systems, providing advantages such as improved launch assist, low-speed creep capability, and driving characteristics similar to a torque-converter/planetary gear-set automatic transmission.

48-volt mild hybrids. Mild hybrids provide idle-stop capability and launch assistance and use a higher voltage battery with increased energy capacity over typical automotive batteries. The higher system voltage allows the use of a smaller, more powerful electric motor than possible with a 12-volt system, and reduces the weight of the motor, inverter, and battery wiring harnesses. This system replaces a standard alternator with an enhanced power, higher voltage, higher efficiency belt-driven starter-alternator which can recover braking energy while the vehicle slows down (regenerative braking). At the time of the FRM, high-voltage (e.g. 120-volt) mild hybrids were known in the market (for example, the Chevrolet Malibu eAssist system), and were anticipated to grow in market share. In the time since the FRM, both mild and strong hybrid sales have not grown as quickly as expected, an outcome that is often attributed to lower fuel prices. Another factor may be the rate of improvements in the efficiency of conventional vehicles, which appear to be closing the fuel economy gap. However, a new generation of mild hybrid technologies is being introduced into the light-duty market, using a 48-volt electrical system, which can reduce costs by eliminating high-voltage safety requirements and battery cooling hardware (in many cases), while offering an effectiveness similar to that of higher-voltage mild hybrids, potentially resulting in significantly greater cost effectiveness. The Draft TAR recognized this trend and added consideration of 48-volt mild hybridization technology.

The following paragraphs outline other technologies that were included in the 2012 FRM and Draft TAR analyses and continue to be included in the Proposed Determination analysis. In many cases the cost, effectiveness, or specific applications of these technologies have also been updated for this analysis. For complete descriptions of the state of development of each technology, please refer to Chapters 2.2.2 through 2.2.10. Specific assumptions for cost and effectiveness for each technology as applied to the Proposed Determination assessment are discussed in Chapter 2.3.4.

Stoichiometric gasoline direct-injection technology. This technology injects fuel at high pressure directly into the combustion chamber to improve cooling of the air/fuel charge within the cylinder, which allows for higher compression ratios and increased thermodynamic efficiency. In the FRM as in the Draft TAR and the current analysis, this technology is projected to be very widespread by 2025.

Exhaust-gas recirculation with boost. Increases the exhaust-gas recirculation used in the combustion process to improve knock-limited operation and reduce pumping losses. Peak levels of exhaust gas recirculation approach 25 percent by volume in these highly boosted engines (this, in turn raises the boost requirement by approximately 25 percent). EPA applies this technology only to 24 bar BMEP and Miller cycle engines.

Low-friction lubricants. Low viscosity and advanced low friction lubricants oils are now available with improved performance and better lubrication.

Second level of low-friction lubricants and engine friction reduction. As technologies continue to advance between now and 2025, we expect further developments enabling lower viscosity and lower friction lubricants and more engine friction reduction technologies available, including the use of roller bearings for balance shaft systems and further improvements to surface treatment coatings. As of MY2017, many of the friction reduction technologies classified as "second level" are already being introduced into light-duty vehicles.

Reduction of engine friction losses. This can be achieved through low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, cylinder wall treatments and other improvements in the design of engine components and subsystems that improve engine operation.

Diesel engines. Despite recent controversy concerning emission control, diesel engines have several characteristics that give superior fuel efficiency, including reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at higher compression and expansion ratios, with a very lean air/fuel mixture, than an equivalent-performance gasoline engine. This technology requires additional enablers, such as use of NOx adsorption exhaust catalyst (NAC), selective catalytic reduction (SCR) of NOx, or a combination of both NAC and SCR NOx catalytic after-treatment and use of a catalyzed diesel particulate filter (CDPF) for PM emissions control.

Improved automatic transmission controls. This technology optimizes the shift schedule to maximize fuel efficiency under wide ranging conditions, and minimizes losses associated with torque converter slip through lock-up or modulation.

Six, seven, and eight-speed (or more) automatic transmissions. Also described here as increased gear-count transmissions, the gear ratio spacing and transmission ratio are optimized to enable the engine to operate in a more efficient operating range over a broader range of vehicle operating conditions. In the FRM, EPA limited its consideration of the effect of additional gears to eight-speed transmissions. However, some ATs with more than eight gears are already in production, and more examples are in development. At this time, nine-speed transmissions are being manufactured by ZF (which produces a FWD nine-speed incorporated into Fiat/Chrysler, Honda, and Jaguar/Land Rover vehicles) and Mercedes (which produces a RWD nine-speed). Ford has released a ten speed transmission in the F150 Raptor, and GM released a variation of the same ten speed in the 2017 Camaro ZL1. In addition, Ford and General Motors have announced plans to jointly design and build a nine-speed FWD transmission, and Honda is developing a ten-speed FWD transmission.

Shift optimization. This technology targets engine operation at the most efficient point for a given power demand. The shift controller emulates a traditional continuously variable transmission by selecting the best gear ratio for fuel economy at a given required vehicle power level to take full advantage of high BMEP engines. The shift controller also incorporates boundary conditions to prevent undesirable operation such as shift busyness and NVH issues.

Manual 6-speed transmission. This technology offers an additional gear ratio, often with a higher overdrive gear ratio, than a 5-speed manual transmission.

High efficiency gearbox (automatic, DCT, CVT, or manual). This technology represents continuous improvement in seals, bearings and clutches, super-finishing of gearbox parts, and development in the area of lubrication, all aimed at reducing friction and other parasitic loads in the system for an automatic, DCT or manual type transmission.

Low-rolling-resistance tires. This technology includes tires that have characteristics that reduce frictional losses associated with the energy dissipated in the deformation of the tires under load, thereby reducing the energy needed to move the vehicle. EPA's analyses have characterized two levels of rolling resistance reduction (LRRT1 and LRRT2), targeting a 10 percent and 20 percent rolling resistance reduction from baseline tires, respectively.

Aerodynamic drag reduction. This technology refers to approaches to reducing aerodynamic drag, which can be achieved by various means such as changing vehicle shapes, reducing frontal area, sealing gaps in body panels, and adding additional components including side trim, air dams, underbody covers, and aerodynamic side view mirrors. EPA's analyses have considered two levels of aerodynamic drag reduction (AERO1 and AERO2), targeting a 10 percent and 20 percent aerodynamic drag reduction, respectively.

Mass reduction. This technology encompasses a variety of techniques ranging from improved design and better component integration to application of lighter and higher-strength materials. In addition to reduced road load, mass reduction can lead to collateral GHG benefits by enabling a downsized engine and/or downsized ancillary systems (transmission, steering, brakes, suspension, etc.) that directly result from the reduced vehicle weight.

Low-drag and zero drag brakes. This technology reduces the sliding friction of disc brake pads on rotors when the brakes are not engaged by pulling the brake pads away from the rotors.

Secondary axle disconnect for four-wheel drive systems. This technology applicable to all-wheel drive systems provides a torque distribution disconnect between front and rear axles when torque is not required for the non-driving axle. This results in the reduction of associated parasitic energy losses.

Electric power steering (EPS). This represents an electrically-assisted steering system that has advantages over traditional hydraulic power steering because it replaces a continuously operated hydraulic pump, thereby reducing parasitic losses from the accessory drive.

Improved accessories (IACC). This represents accessories with improved efficiency. EPA's analyses have considered two levels of IACC. The first level may include high efficiency alternators, electrically driven (i.e., on-demand) water pumps and cooling systems. This excludes other electrical accessories such as electric oil pumps and electrically driven air conditioner compressors. The second level of IACC includes alternator regenerative braking on top of what are included in the first level of IACC.

Low-leakage and higher-efficiency air conditioner systems. These technologies are focused on reducing leakage of high-GWP refrigerants and improved energy efficiency. Leakage measures include improved hoses, connectors and seals for leakage control. Efficiency measures include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO_2 emissions and fuel economy when the A/C is operating.

Non-hybrid stop-start. Also known as idle-stop or 12V micro hybrid, this is the most basic system that facilitates idle-stop capability. This system includes an enhanced performance starter and battery but no additional hybridization features. While stop-start has been in production for a considerable amount of time in Europe (a predominantly manual transmission market), some of the initial product offerings in the U.S. met with consumer feedback concerns.

Since the FRM, some recent vehicles were introduced with stop-start implementations that were specifically designed for the U.S. market, such as the Chevrolet Malibu, and have been met with very good reviews. Indications from suppliers are that further improvements, including the use of continuously engaged starters, are under development.

Strong hybrids (P2 hybrid). Strong hybrids include what are known as P2 hybrids and power-split hybrids, among other types. EPA models strong hybrids as P2 hybrids. The P2 hybrid is a technology that uses a transmission-integrated electric motor placed between the engine and a gearbox or CVT, with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. A P2 hybrid would typically be equipped with a larger electric machine than a mild hybrid system, but smaller than a power-split hybrid architecture. Disengaging the clutch allows all-electric operation and more efficient brake-energy recovery. Engaging the clutch allows efficient coupling of the engine and electric motor and based on simulation, when combined with a DCT transmission, provides similar efficiency to other strong hybrid systems.

Power-split Hybrid (PSHEVs). While EPA models primarily P2 hybrids in this analysis, power-split hybrids are represented in the baseline fleet. Power split is a hybrid electric drive system that replaces the traditional transmission with a single planetary gearset and two motor/generators. One motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. The second, usually more powerful, motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels, as well as providing regenerative braking capability. The planetary gear-set splits engine power between the first motor/generator and the output shaft to either charge the battery or supply power to the wheels. The Power-split hybrid provides similar efficiency to other strong hybrid systems.

Plug-in hybrid electric vehicles (PHEVs). Hybrid electric vehicles with the means to charge their battery packs from an outside source of electricity (usually the electric grid). These vehicles have larger battery packs than non-plug-in hybrid electric vehicles with more energy storage and a greater capability to be discharged. They also use a control system that allows the battery pack to be substantially depleted under electric-only or blended mechanical/electric operation, allowing for reduced fuel use during "charge depleting" operation. The FRM, Draft TAR and this Proposed Determination analysis models PHEVs with 20-mile and 40-mile ranges.

Battery electric vehicles (BEVs). Vehicles with all-electric drive and with vehicle systems powered by energy-optimized batteries charged from an outside source of electricity (usually the electric grid). In the FRM, BEVs were modeled with driving ranges of 75 miles, 100 miles, and 150 miles. The Draft TAR revised the 150-mile BEV to a 200-mile BEV, which is retained for this analysis.

In summary, this Chapter 2.2.1 has provided only a brief outline of the fuel-saving and GHG-reducing technologies considered in the Proposed Determination analysis. For complete descriptions of the state of development of each technology, please refer to Chapters 2.2.2 through 2.2.10. Specific assumptions for cost and effectiveness for each technology are discussed in Chapter 2.3.4.

2.2.2 Engines: State of Technology

Internal combustion engine improvements continue to be a major focus in improving the overall efficiency of light-duty vehicles. While the primary type of light-duty vehicle engine in the United States is a gasoline fueled, spark ignition (SI), port-fuel-injection (PFI) design, it is undergoing a significant evolution as manufacturers work to improve engine brake thermal efficiency (BTE) from what has historically been approximately 25 percent to BTE of 37 percent and above. This focus on improving gasoline SI engines has resulted in the adoption of technologies such as gasoline direct injection (GDI), turbo-charging and downsizing, Atkinson Cycle, Miller Cycle, increased valve control authority through variable valve timing and variable valve lift, integrated exhaust manifolds, reduced friction, and cooled EGR (cEGR). Vehicle manufacturers have more choices of technology for internal combustion engines than at any previous time in automotive history and more control over engine operation and combustion. In addition, manufacturers have access to improved design tools that allow them to investigate and simulate a wide range of technology combinations to allow them to make the best decisions regarding the application of technology into individual vehicles. Despite the access to improved tools and simulation, EPA believes that manufacturers have not yet explored the entire design space of modern powertrain architectures and that innovation will continue resulting in improvements in efficiency that are beyond what is currently being demonstrated in the new car fleet.

As discussed in Chapter 3, the use of many of the major powertrain technologies analyzed in the 2012 FRM, including engine technologies such as VVT, direct injection, turbocharging, and cylinder deactivation have increased since the publication of the FRM and appear to be trending towards EPA projections of technology penetration levels from the 2017-2025 FRM analysis (see Chapter 3). Engines equipped with GDI are projected to achieve a 46 percent market share in MY2015. Approximately 18 percent of new vehicles are projected to be equipped with turbochargers for MY2015. Use of cylinder deactivation has grown to capture a projected 13 percent of light-duty vehicle production for MY2015. Light duty diesel vehicles are projected to increase to a projected 1.5 percent of new vehicle production for MY2015, which is the highest level since MY1984. Recently introduced light-duty diesels in the U.S. include several new pickup truck (2015 Ram 1500, 2016 Chevrolet Colorado, 2016 GMC Canyon) and SUV (2015 Jeep Grand Cherokee, 2016 Land Rover Range Rover, Mercedes GLE300 and GLE350) models. Mazda has transitioned all of their products to either Atkinson Cycle or Miller Cycle engines. Volkswagen's entire gasoline vehicle product range uses downsized/turbocharged/GDI engines and most of these engine families are now transitioning to Miller Cycle.

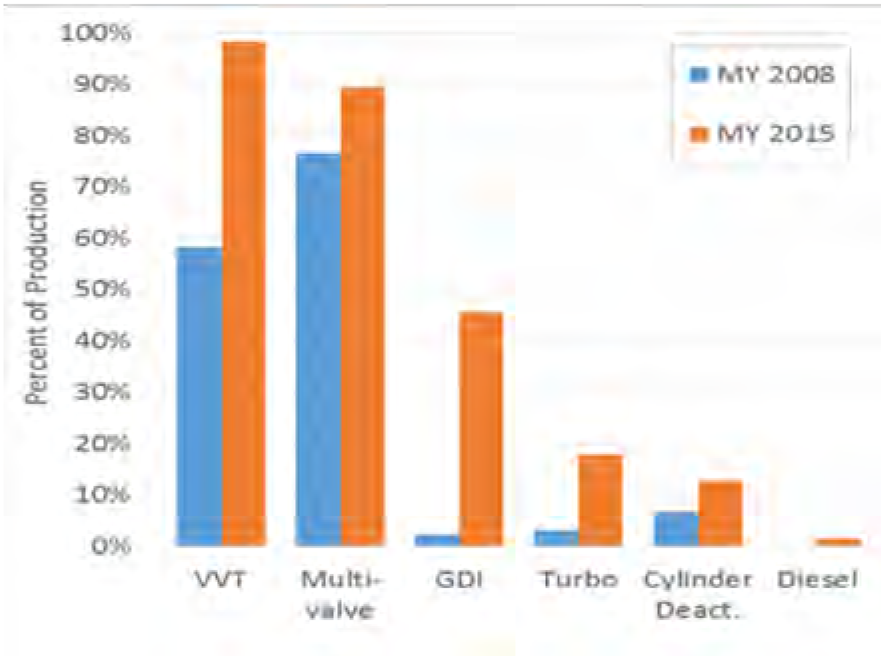


Figure 2.1 Light-duty Vehicle Engine Technology Penetration since the 2012 Final Rule

2.2.2.1 Overview of Engine Technologies

Since the FRM, to prepare for the Draft TAR the agencies met with automobile manufacturers, major Tier 1 automotive suppliers and major automotive engineering services firms to review both public and confidential data on the development of advanced internal combustion engines for MY2022 and later. A considerable amount of new work was completed both within the agencies and within industry and academia that was therefore available for consideration in the Draft TAR. EPA completed several engine benchmarking programs that have produced detailed engine maps. These engine maps represent some of the best performing engines available today and have been used in the ALPHA model to directly estimate the effectiveness of modern powertrain technology being applied to a wide spectrum of vehicle applications. In addition, industry and academia regularly publishes similar levels of detail with regard to engine operation in the public domain, and EPA has also used this information to either directly inform or to compare effectiveness estimations.

In addition to creating detailed engine maps for full vehicle simulation, EPA conducted proof-of-concept, applied research to investigate the potential for further engine improvements. This includes the use of both computer-aided engineering tools and the development and analysis of advanced engine technologies via engine dynamometer testing. Further details are provided in Chapter 2.3.

In the time since the FRM, in meetings with automobile manufacturers and Tier 1 suppliers, we learned about convergent and divergent trends in engine technologies. Through this ongoing analysis and OMEGA modeling, it continues to be our assessment that through MY2022, with few exceptions, gasoline direct injection and VVT will be applied to most engines. Significant attention will be placed on reducing engine friction and accessory parasitic loads. In passenger car and smaller light-duty truck segments, there will be considerable diversity of engine technologies, including turbocharged GDI engines with up to 25-bar BMEP, both turbocharged and naturally aspirated GDI engines with external cooled EGR, engines that combine GDI with operation over the Atkinson Cycle, use of Atkinson Cycle in non-HEV applications, and use of Miller Cycle (boosted Atkinson Cycle). With respect to larger, heavier vehicles, including full-size SUVs and pickup trucks with significant towing utility, some manufacturers will be relying on naturally aspirated GDI engines with cylinder deactivation, some will be relying more on turbocharged-downsized engines, and others will be using a variety of engine technologies, including light-duty diesels. Vehicle manufacturers are at advanced stages of research with respect to:

- Stratified-charge, lean-burn combustion
- Multi-mode combustion approaches
  - homogenous charge, compression ignition, lean-burn operation at light loads
  - stratified-charge, lean-burn spark ignition at moderate loads
  - stoichiometric homogenous charge, spark ignition at high loads
- Variable-compression ratio (VCR) engines
- Engines exceeding 24-bar BMEP

While the introduction of variable compression ratio engines and highly boosted GDI engines above 24-bar BMEP is expected within the 2022-2025 time frame, these technologies will most likely be introduced into relatively low-volume, high performance applications. Manufacturers and suppliers are finding that turbocharged engines can achieve lower CO_2 emissions over the regulatory drive cycles and improved real-world fuel economy at more moderate (24 bar and below) BMEP levels. While there are both performance and efficiency advantages to VCR at high BMEP levels, both Atkinson Cycle and Miller Cycle with VVT are technologies that compete with VCR and that have a comparable ability to vary effective compression ratio but with reduced cost and complexity.

We also learned from manufacturers and suppliers that specific engine technologies have synergies with other CO_2-reduction technologies. For example, measures to reduce engine friction, particularly friction at startup, help reduce the motor torque necessary for restart in 12V start/stop systems. GDI and electric cam phasing systems can be used for combustion assistance of engine restart. There are also synergies between Miller Cycle, IEM, cooled-EGR, and the use of VNT turbochargers which are described in more detail in Chapter 2.2.2.7.

Despite recent EPA and California ARB compliance actions with respect to light-duty diesel NOx emissions, diesel engines remain a technology for the reduction of GHG emissions from light-duty vehicles. Advances in NOx and PM emissions control technology are bringing light-duty diesels fully into compliance with Federal Tier 3 and California LEV III emissions standards at a cost that is competitive with the cost-effectiveness other high efficiency, advanced engine technologies. In the FRM, diesel powertrains were not expected to be a significant technology for improving vehicle efficiency, however, since then many new light-duty vehicles have been introduced to the U.S. market with diesel engines, including the Ram 1500 full-size pickup truck, the Chevrolet Colorado mid-size pickup truck, the Jeep Grand Cherokee SUV, and the Chevrolet Cruze. In addition, diesel engines are continuing to evolve using technologies similar to those being introduced in new light-duty gasoline engines and heavy-duty diesel truck engines, including the use of advanced friction reduction measures, increased turbocharger boosting and engine downsizing, use of VNT and/or sequential turbocharging, engine "downspeeding," the use of advanced cooled EGR systems, improved integration of charge air cooling into the air intake system, and improved integration of exhaust emissions control systems for criteria pollutant control. The best BTE of advanced diesel engines under development for light duty applications is now 46 percent and thus is approaching that of heavy-duty diesel truck engines.[2]

In addition to a reevaluation of all of the cost and effectiveness values of the technologies that were considered in the FRM, this TSD (as did the Draft TAR) includes evaluations of technologies where substantial new information has emerged since the FRM, including Atkinson and Miller cycle engines, and application of cylinder deactivation operation to 3-cylinder, 4-cylinder, and turbocharged engines.

2.2.2.2 Sources of Engine Effectiveness Data

In addition to the sources of engine CO_2 effectiveness data used in the 2017-2025 LD GHG FRM, EPA also used engine data from a wide range of sources to update engine effectiveness for the draft TAR and Proposed Determination, including:

- Publicly available data (e.g., peer-reviewed journals, peer-reviewed technical papers, conference proceedings)
- Data directly acquired by EPA via engine dynamometer testing at EPA-NVFEL or at contract laboratories
- Benchmarking and simulation modeling of current and future engine configurations
- Confidential data from OEMs, Tier 1 suppliers, and major automotive engineering services firms
- Data from the U.S. Department of Energy Vehicle Technologies Program

A considerable amount of brake-specific fuel consumption (BSFC), brake-thermal efficiency (BTE) and chassis-dynamometer drive cycle fuel consumption data for advanced powertrains has been published in journals, technical papers and conference proceedings since the publication of the 2012 FRM. In some cases, published data includes detailed engine maps of BSFC and/or BTE over a wide area of engine operation. In addition, these publications provide a great deal of information regarding the specific design changes made to an engine which allow the engine to operate at an improved BSFC and vehicles to operate with improved fuel consumption. These design details often include changes to engine friction, changes to valvetrain and valve control, combustion chamber design and combustion control, boosting components and boosting control, and exhaust system modifications. This information provides the agency an indication of which technologies to investigate in more detail and offers the opportunity to correlate testing and simulation results against currently available and future designs.

Since 2012, many examples of advanced engine technologies have gone into production for the U.S., European and Japanese markets. EPA has acquired many vehicles for chassis dynamometer testing and has developed a methodology for conducting detailed engine dynamometer testing of engines and engine/transmission combinations. Engine dynamometer testing was conducted both at the EPA-NVFEL facility in Ann Arbor, MI and at other test facilities under contract with EPA. Engine dynamometer testing of production engines outside of the vehicle chassis required the use of a vehicle-to-engine (or vehicle-to-engine/transmission) wiring tether and simulated vehicle feedback signals in order to allow use of the vehicle manufacturer's engine management system and calibrated control parameters. In addition to fuel consumption and regulated emissions, many of the engines were also instrumented with piezo-electric cylinder pressure transducers and crankshaft position sensors to allow calculation of the apparent rate of heat release and combustion phasing. Engines with camshaft-phasing were also equipped with camshaft position sensors to allow monitoring of the timing of valve events. Engine dynamometer testing also incorporated hardware-in-the-loop HIL simulation of drive cycles so that vehicle packages with varying transmission configurations and road-loads could be evaluated. Specific examples of engine benchmarking and HIL simulation used by EPA were published within peer reviewed literature prior to release of the Draft TAR.[3]

While the confidential data provided by vehicle manufacturers, suppliers and engineering firms cannot be published in the Draft TAR, these sources of data were important as they allowed EPA to perform quality and rationality checks against the data that we are making publicly available. In each case where a specific technology was benchmarked, EPA met with the vehicle manufacturer to confirm the results. In cases where expected combinations of future engine technologies were not available for testing from current production vehicles, a combination of proof-of-concept engine dynamometer testing and engine and vehicle CAE simulations were used to determine drive cycle effectiveness. For example, use of cooled EGR and an increased geometric compression ratio was modeled using Gamma Technologies GT-Power simulations of combustion and gas dynamics with subsequent engine dynamometer validation conducted using a prototype engine management system, a developmental external low-pressure cooled EGR system, and a developmental dual-coil offset ignition system. Finally, several of these benchmarking activities were the subject of technical papers published by SAE and included a peer review of the results as part of the publication process.

2.2.2.3 Low Friction Lubricants (LUB)

One of the most basic methods of reducing fuel consumption in gasoline engines is the use of lower viscosity engine lubricants. More advanced multi-viscosity engine oils are available today with improved performance in a wider temperature band and with better lubricating properties. This can be accomplished by changes to the oil base stock (e.g., switching engine lubricants from a Group I base oils to lower-friction, lower viscosity Group III synthetic) and through changes to lubricant additive packages (e.g., friction modifiers and viscosity improvers). The use of 5W-30 motor oil is now widespread and auto manufacturers are introducing the use of even lower viscosity oils, such as 5W-20 and 0W-20, to improve cold-flow properties and reduce cold start friction. However, in some cases, changes to the crankshaft, rod and main bearings and changes to the mechanical tolerances of engine components may be required. In all cases, durability testing is required to ensure that durability is not compromised. The shift to lower viscosity and lower friction lubricants also improve the effectiveness of valvetrain technologies such as cylinder deactivation, which rely on a minimum oil temperature (viscosity) for operation.

2.2.2.4 Engine Friction Reduction (EFR1, EFR2)

In addition to low friction lubricants, manufacturers can also reduce friction and improve fuel consumption by improving the design of engine components and subsystems. Approximately 10 percent of the energy consumed by a vehicle is lost to friction, and just over half is due to frictional losses within the engine. Examples include improvements in low-tension piston rings, piston skirt design, roller cam followers, improved crankshaft design and bearings, material coatings, material substitution, more optimal thermal management, and piston and cylinder surface treatments. Additionally, as computer-aided modeling software continues to improve, more opportunities for evolutionary friction reductions may become available.

All reciprocating and rotating components in the engine are potential candidates for friction reduction, and minute improvements in several components can add up to a measurable fuel economy improvement.

2.2.2.5 Cylinder Deactivation (DEAC)

In conventional spark-ignited engines throttling the airflow controls engine torque output. At partial loads, efficiency can be improved by using cylinder deactivation instead of throttling. Cylinder deactivation (DEAC) can improve engine efficiency by disabling or deactivating cylinders when the load is significantly less than the engine's total torque capability – the valves are kept closed, and no fuel is injected – as a result, the trapped air within the deactivated cylinders is simply compressed and expanded as an air spring, with reduced friction and heat losses. The active cylinders combust at higher loads to compensate for the deactivated cylinders. Pumping losses are significantly reduced as long as the engine is operated in this "part-cylinder" mode.

Cylinder deactivation control strategy relies on setting maximum manifold absolute pressures or predicted torque within which it can deactivate the cylinders. Noise and vibration issues reduce the operating range to which cylinder deactivation is allowed, although manufacturers continue exploring vehicle and engine changes that enable increasing the amount of time that cylinder deactivation might be suitable. Some manufacturers have adopted active engine mounts, active noise cancellations systems, and crankshaft dampening systems to address NVH concerns and to allow a greater operating range of activation.

2.2.2.6 Variable Valve Timing (VVT) Systems

Variable valve timing (VVT) is a family of valve-train designs that alter the timing of the intake valve, exhaust valve, or both, primarily to reduce pumping losses, increase specific power, and control the level of residual gases in the cylinder. VVT reduces pumping losses when the engine is lightly loaded by controlling valve timing closer to an optimum needed to sustain horsepower and torque. VVT can also improve volumetric efficiency at higher engine speeds and loads. Additionally, VVT can be used to alter (and optimize) the effective compression ratio where it is advantageous for certain engine operating modes (e.g., in the Atkinson Cycle).

VVT has now become a widely adopted technology. In MY2015, more than 98 percent of light-duty vehicles sold in the U.S. are projected to use some form of VVT.[195] The three major types of VVT are listed in the sub-sections below.

Each of the three implementations of VVT uses a cam phaser to adjust the camshaft angular position relative to the crankshaft position, referred to as "camshaft phasing." The phase adjustment results in changes to the pumping work required by the engine to accomplish the gas exchange process. The majority of current cam phaser applications use hydraulically-actuated units, powered by engine oil pressure and managed by a solenoid that controls the oil pressure supplied to the phaser. Electric cam phasing allows a wider range of camshaft phasing, faster time-to-position, and allows adjustment of camshaft phasing under conditions that can be challenging for hydraulic systems, for example, during and immediately after engine startup.

2.2.2.6.1 Intake Cam Phasing (ICP)

Valvetrains with ICP can modify the timing of the inlet valves by phasing the intake camshaft while the exhaust valve timing remains fixed. This requires the addition of a cam phaser on each bank of intake valves on the engine. An in-line 4-cylinder engine has one bank of intake valves, while V-configured engines have two banks of intake valves.

2.2.2.6.2 Coupled Cam Phasing (CCP)

Valvetrains with coupled (or coordinated) cam phasing can modify the timing of both the inlet valves and the exhaust valves an equal amount by phasing the camshaft of a single overhead cam (SOHC) engine or a cam-in-block, overhead valve (OHV) engine. For overhead cam engines, this requires the addition of a cam phaser on each bank of the engine. Thus, an in-line 4-cylinder engine has one cam phaser, while SOHC V-engines have two cam phasers. For overhead valve (OHV) engines, which have only one camshaft to actuate both inlet and exhaust valves, CCP is the only VVT implementation option available and requires only one cam phaser.

2.2.2.6.3 Dual Cam Phasing (DCP)

The most flexible VVT design is dual (independent) cam phasing, where the intake and exhaust valve opening and closing events are controlled independently. This option allows the option of controlling valve overlap, which can be used as an internal EGR strategy. At low engine loads, DCP creates a reduction in pumping losses, resulting in improved fuel consumption/reduced CO_2 emissions. Increased internal EGR also results in lower engine-out NOx emissions. The amount by which fuel consumption is improved and CO_2 emissions are reduced depends on the residual tolerance of the combustion system and on the combustion phasing achieved. Additional improvements are observed at idle, where smaller valve overlap could result in improved combustion stability, potentially reducing idle fuel consumption.

2.2.2.6.4 Variable Valve Lift (VVL)

Controlling the lift of the valves provides a potential for further efficiency improvements. By optimizing the valve-lift profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. By moving the throttling losses further downstream of the throttle valve, the heat transfer losses that occur from the throttling process are directed into the fresh charge-air mixture just prior to compression, delaying the onset of knock-limited combustion. Variable valve lift control can also be used to induce in-cylinder mixture motion, which improves fuel-air mixing and can result in improved thermodynamic efficiency. Variable valve lift control can also potentially reduce overall valvetrain friction. At the same time, such systems may incur increased parasitic losses associated with their actuation mechanisms. A number of manufacturers have already implemented VVL into all (BMW) or portions (Toyota, Honda, and GM) of their fleets, but overall this technology is still available for application to most vehicles. There are two major classifications of variable valve lift, discrete variable valve lift (DVVL) and continuous variable valve lift (CVVL).

DVVL systems allow the selection between two or three discrete cam profiles by means of a hydraulically-actuated mechanical system. By optimizing the cam profile for specific engine operating regions, the pumping losses can be reduced by reducing the amount of throttling required to produce the desired engine power output. This increases the efficiency of the engine.

These cam profiles may consist of a low and a high-lift lobe or other combinations of cam profiles, and may also include an inert or blank lobe to incorporate cylinder deactivation (in the case of a 3-step DVVL system). DVVL is normally applied together with VVT control. DVVL is also known as Cam Profile Switching (CPS). DVVL is a mature technology with low technical risk.

In CVVL systems, valve lift is varied by means of a mechanical linkage, driven by an actuator controlled by the engine control unit. The valve opening and phasing vary as the lift is changed and the relation depends on the geometry of the mechanical system. BMW has considerable production experience with CVVL systems and has versions of its "Valvetronic" CVVL system since 2001. CVVL allows the airflow into the engine to be regulated by means of intake valve opening reduction, which improves engine efficiency by reducing pumping losses from throttling the intake system further upstream as with a conventionally throttled engine. CVVL provides greater effectiveness than DVVL, since it can be fully optimized for all engine speeds and loads, and is not limited to a two or three step compromise. There may also be a small reduction in valvetrain friction when operating at low valve lift, resulting in improved low load fuel consumption for cam phase control with variable valve lift as compared to cam phase control only. Most of the fuel economy effectiveness is achieved with variable valve lift on the intake valves only. CVVL is typically only applied to double overhead cam (DOHC) engines.

2.2.2.7 GDI, Turbocharging, Downsizing and Cylinder Deactivation

Between 2010 and 2015, automotive manufacturers have been adopting advanced powertrain technologies in response to GHG and CAFE standards. Just over 45 percent of MY2015 light-duty vehicles in U.S. were equipped with gasoline direct injection (GDI) and approximately 18 percent of MY2015 light-duty vehicles were turbocharged.[4] Nearly all vehicles using turbocharged spark-ignition engines also used GDI to improve suppression of knocking combustion. GDI provides direct cooling of the in-cylinder charge via in-cylinder fuel vaporization.[5] Use of GDI allows an increase of compression ratio of approximately 0.5 to 1.5 points relative to naturally aspirated or turbocharged engines using port-fuel-injection (e.g., an increase from 9.9:1 for the 5.3L PFI GM Vortec 5300 to 11:1 for the 5.3L GDI GM Ecotec3 with similar 87 AKI gasoline octane requirements).

Figure 2.2 shows a comparison of brake thermal efficiency (BTE) versus engine speed and load between a high-volume, MY2008 2.4L I4 engine equipped with PFI and a MY2013 GM Ecotec^{TM} 2.5L I4 equipped with GDI. The GDI engine has a significantly higher compression ratio, (11.3:1 vs 9.6:1), higher efficiency throughout its range of operation, and achieves higher BMEP levels (approximately 12.5 bar vs 11.3 bar), allowing a significant increase in power per displacement. The incremental effectiveness at approximately 2-bar BMEP and 2000 rpm was 17 percent but varied from approximately 3 percent to approximately 11 percent at other speed and load points of importance for the regulatory drive cycles.

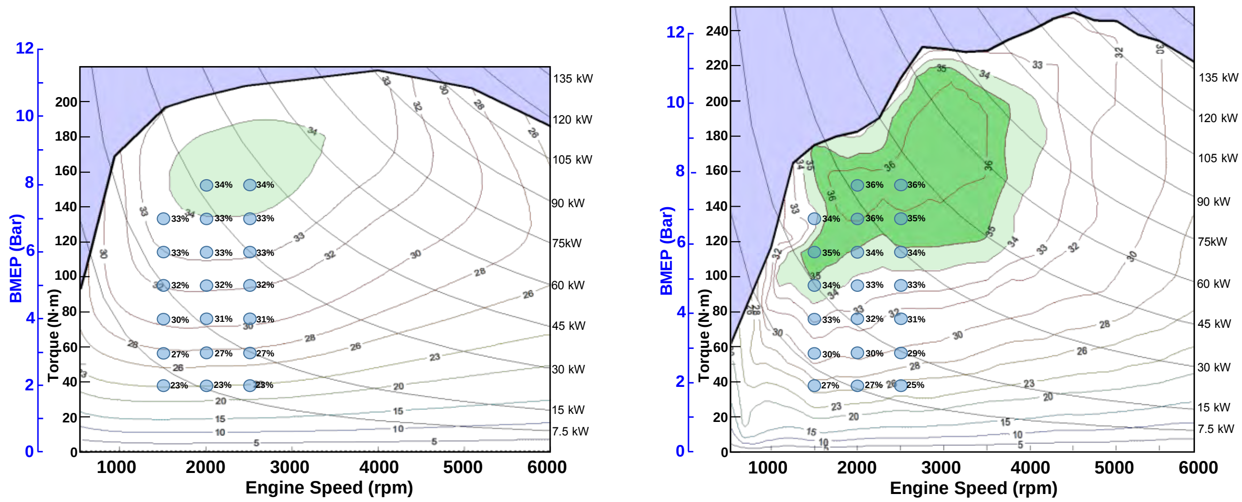


Figure 2.2 Comparison of BTE for A Representative MY2008 2.4L I4 NA DOHC PFI 4-valve/cyl. Engine with Intake Cam Phasing (Left)[C] and a GM Ecotec 2.5L NA GDI Engine with Dual Camshaft Phasing (Right).[D]

Note: Area of Operation > 34% BTE is Shown in Light Green. Area of Operation >35% BTE is Shown in Dark Green.

Toyota's D-4S system combines GDI and PFI systems, with two injectors per cylinder (one directly in-cylinder and one immediately upstream of the intake port).[6,7,8] As of 2015, all Toyota vehicles in the U.S. with GDI appear to be using a variation of the D-4S dual GDI/PFI fuel injection system. This system increases peak BMEP, provides additional flexibility with respect to calibration of the EMS for improved cold-start emissions and offers an efficiency improvement over GDI alone. Based on certification data and EPA confirmatory test data, Toyota vehicles using engines equipped with the D4S system have relatively low PM emissions over the FTP75 cycle that are roughly comparable to PFI-equipped vehicles (<0.60 mg/mi).[9] A comparison of the Toyota 2GR-FSE engine is shown compared to a 3.5L PFI engine in Figure 2.3. The 2GR-FSE achieves a very high BMEP for a naturally aspirated engine (13.7 bar). Although both engines have comparable displacement, they are not directly comparable because the higher BMEP attained by the 2GR-FSE would allow further engine downsizing for a similar application, with potential for further improvement in BTE at light load relative to the 3.5L PFI engine. The area greater than 34 percent BTE is significantly larger for the Toyota 2GR-FSE due to a combination of factors, including a higher compression ratio enabled by GDI and reduced pumping losses through use of a dual camshaft phasing system that enables reduced throttling and internal EGR at light loads.

[C] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.

[D] Based on EPA engine dynamometer test data.

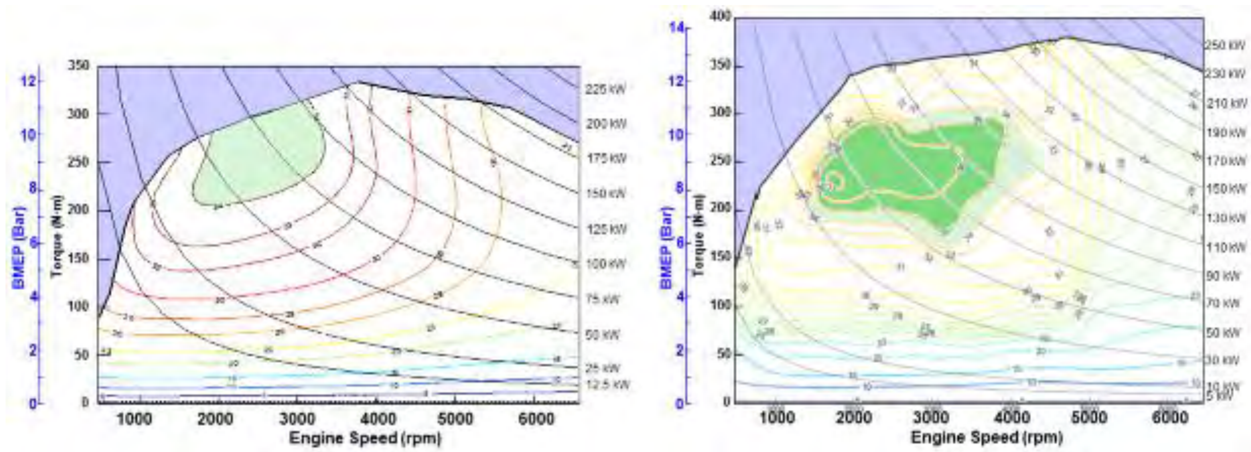


Figure 2.3 Comparison of BTE for A Representative MY2010 3.5L V6 NA PFI 4-valve/cyl. Engine[E] (Left) and a Toyota 2GR-FSE GDI/PFI Engine with Dual Camshaft Phasing[F] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green.

The recently redesigned Ford turbocharged 3.5L "EcoBoost™" engine in the 2017 Ford F150 also uses a dual GDI/PFI injection system to increase power, reduce emissions, and improve efficiency,[10] but other engines in Ford's EcoBoost lineup use GDI alone. In MY2015, Ford offered a version of the EcoBoost turbocharged GDI engines as standard or optional engines in nearly all of models of light-duty cars and trucks. Ford's world-wide production of EcoBoost engines exceeded 200,000 units per month during CY2015.[11]

Approximately 13 percent of MY2015 light-duty vehicles used cylinder deactivation, primarily in light-duty truck applications. In MY2015, General Motors introduced their “Ecotec3” line of OHV V6 and V8 engines across their entire lineup of light-duty pickups and truck-based SUVs. These engines are equipped with GDI, coupled-cam-phasing, and cylinder deactivation. Both the V6 and V8 EcoTec3 engines are capable of operation on 4-cylinders under light-load conditions. Application of GDI has synergies with cylinder deactivation. The higher BMEP achievable with GDI also increases the BMEP achievable once cylinders have been deactivated, thus increasing the range of operation where cylinder deactivation is enabled.

Cylinder deactivation operates the remaining, firing cylinders at higher BMEP under light load conditions. This moves operation of the remaining cylinders to an area of engine operation with less throttling and thus lower pumping losses (Figure 2.4) and reduced BSFC.

[E] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.

[F] Based on EPA engine dynamometer test data.

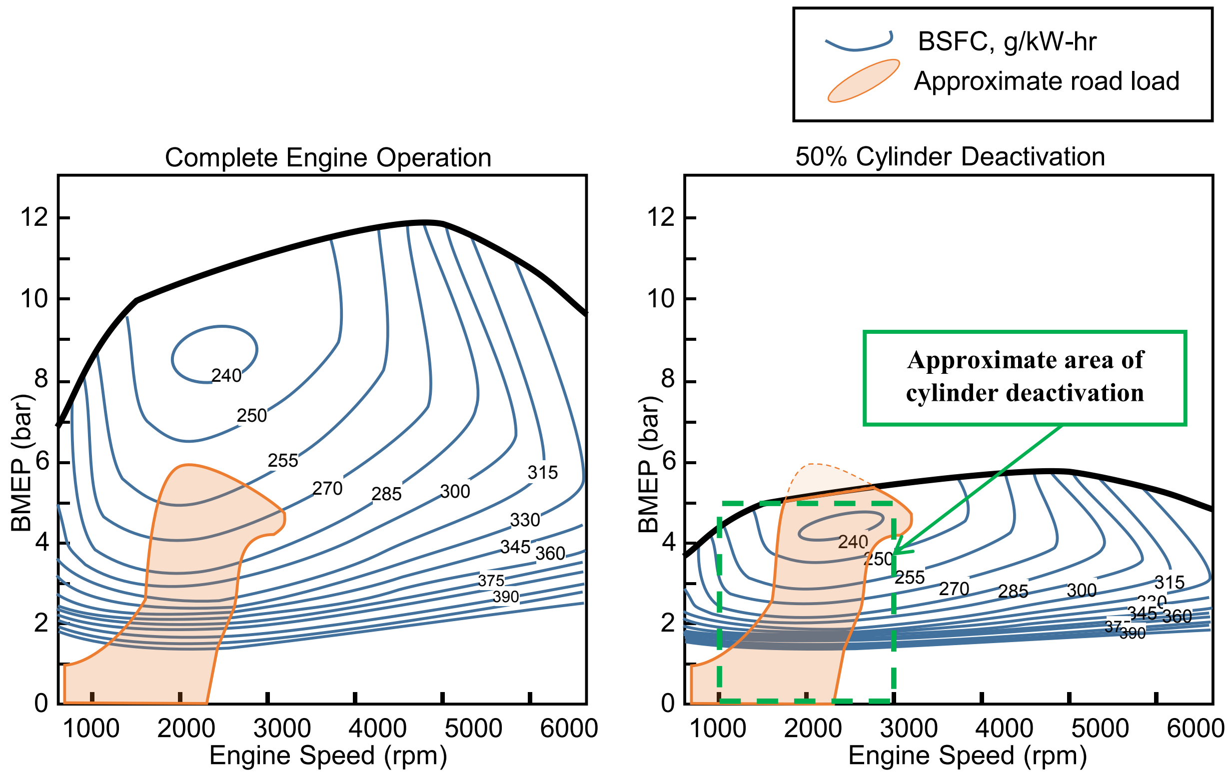


Figure 2.4 Graphical Representation Showing How Cylinder Deactivation Moves Engine Operation to Regions of Operation with Improved Fuel Consumption over the UDDS Regulatory Drive Cycle (shaded area).

Since 2012, improvements in crankshaft dampening systems have extended the application of cylinder deactivation to four cylinder engines. Volkswagen introduced their 1.4L TSI EA 211 turbocharged GDI engine with "active cylinder management" in Europe for MY2013.[12] This engine is the first production application of cylinder deactivation to an I4 engine and can deactivate 2 cylinders via cam-shifting under light load conditions. VW recently introduced a Miller Cycle variant of the same EA211 engine family with cylinder deactivation (1.5L EA 211 evo).[13] Schaeffler has developed a dynamic cylinder deactivation system for I3 and I5 engines that alternates or "rolls" the deactivated cylinders. This system allows all cylinders to be deactivated after every ignition cycle and reactivated during the next cycle. Cylinder deactivation thus alternates within a single deactivation phase and not each time a new deactivation mode is introduced. The net result is that engines with an odd number of cylinders can operate, on average, with half their cylinder displacement (i.e., I3 can drop to 1.5 cylinders on average or an I5 can drop to 2.5 cylinders on average). Ford and Schaeffler investigated both rolling cylinder deactivation and a system to deactivate one cylinder with Ford's EcoBoost 1.0L I3 engine and found that, with appropriate vibrational dampening, either strategy could be implemented with no NVH deterioration and with 3 percent or greater improvement in both real-world and EU drive cycle fuel economy.[14] Tula Technology has demonstrated a system with the capability of deactivating any cylinder that they refer to as "Dynamic Skip Fire."[15] Tula found a combined-cycle fuel economy improvement of approximately 14 percent for an unspecified vehicle equipped with a 6.2L PFI V8 and approximately 6 percent for an application equipped with the GM Active Fuel Management 4/8 cylinder deactivation system. It should be noted that engines with more opportunity for pumping loss reduction over the regulatory drive cycles (e.g., larger displacement, naturally aspirated, PFI) generally have higher CO_2 effectiveness when equipped with cylinder deactivation.

Many automotive manufacturers have launched a third or fourth generation of GDI engines since their initial introduction in the U.S. in 2007. Turbocharged, GDI engines are in now in volume production at between 21-bar and 25-bar BMEP. Most recent turbocharged engine designs now use head-integrated, water-cooled exhaust manifolds and coolant loops that separate the cooling circuits between the engine block and the head/exhaust manifold(s). Head-integrated exhaust manifolds (IEM) are described further in the section on thermal management in 2.2.2.11. The use of IEM was assumed within the EPA analysis of 27-bar BMEP turbocharged GDI engines for the FRM. The benefits, including increased ability to downspeed the engine without pre-ignition and the potential for cost savings in the design of the turbocharger turbine housing appear to extend to lower BMEP-level turbocharged GDI engines and will likely be incorporated into many future turbocharged light-duty vehicle applications. The application of IEMs does effect cooling system design and manufacturers will be required to provide sufficient cooling system capacity if they adopt this technology.

The 2.7L Ford EcoBoost engine was introduced in the MY2015 Ford F150. This engine uses one turbocharger per bank, IEM and dual camshaft phasing. Peak BMEP is approximately 24-bar and the maximum towing capacity of the F150 equipped with this engine is 13,300 lbs. when used with a 3.73:1 final drive ratio in the 2016 Ford F150. Figure 2.5 shows a comparison of BMEP and torque vs. engine speed and BTE between a conventional MY2010 5.4L OHC V8 light-duty pickup truck engine and the MY 2015 2.7L Ford EcoBoost engine. This comparison thus represents 50 percent engine downsizing using turbocharging and GDI. The 2.7L EcoBoost engine has higher peak torque and power, higher peak BTE, and approximately double the area above 34 percent BTE. Figure 2.6 shows data from operation of a 2015 Ford F150 with a 2.7L EcoBoost engine operated over the UDDS (City Cycle) and HWFET (Highway Cycle) superimposed over the BTE data from engine dynamometer testing. Turbocharging and downsizing along with proper selection of transmission and final drive gear ratios and shifting strategy moves results in operation over the regulatory drive cycles that are more closely aligned with regions of higher BTE.

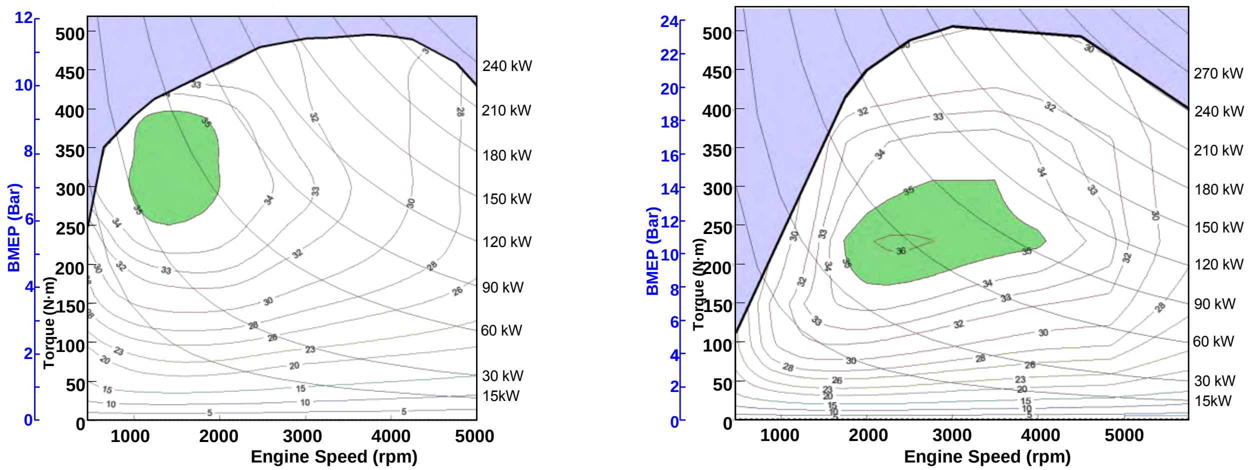


Figure 2.5 Comparison of BTE for A Representative MY2010 5.4L V8 NA PFI 3-valve/cyl. Engine[G] (Left) and a Ford 2.7L V6 EcoBoost Turbocharged, GDI Engine With Dual Camshaft Phasing[H] (Right).

Note: Area of Operation > 35% BTE is Shown in Green.

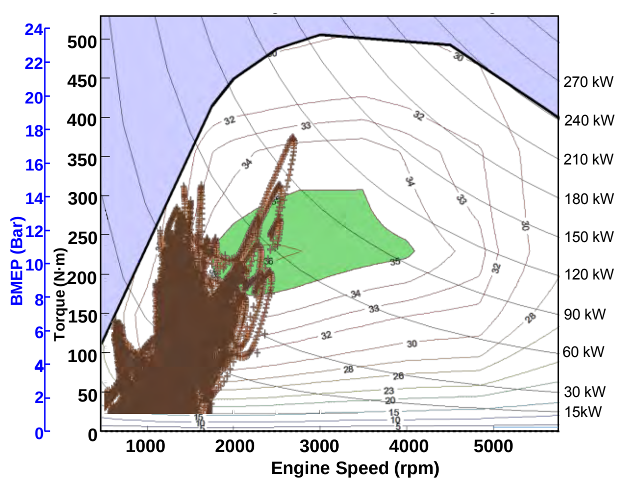


Figure 2.6 Engine Speed and BMEP Points Taken from 10 Hz-sampled data over the UDDS and HWFET[I] Superimposed Over BTE Data From a Ford 2.7L V6 EcoBoost Turbocharged, GDI Engine With Dual Camshaft Phasing[J] (Right).

Figure 2.7 shows maps of BMEP and torque vs. engine speed and BTE for a representative MY2010 2.4L PFI engine with intake camshaft phasing and a MY2012 1.0L Ford EcoBoost turbocharged, GDI, engine with an integrated exhaust manifold (IEM) and dual camshaft phasing.[16] The 1.0L EcoBoost engine also has a peak BMEP of 25-bar and center-mounted, spray-guided fuel injection. While not a direct comparison for purposes of engine downsizing (the 1.0L EcoBoost is more comparable to a 1.8 – 2.0L NA PFI engine based on torque

[G] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.

[H] Based on EPA engine dynamometer test data.

[I] Based on EPA Chassis dynamometer data.

[J] Based on EPA engine dynamometer test data.

characteristics and rated power), this comparison of BTE does demonstrate the manner that turbocharging and downsizing can be used to expand regions of high thermal efficiency to cover a larger portion of engine operation. For example, the EcoBoost engine exceeds 30 percent BTE above 6-bar BMEP/50 N-m torque over most of the engine's range of engine speeds while the area above 30 percent BTE for the NA PFI engine is considerably smaller.

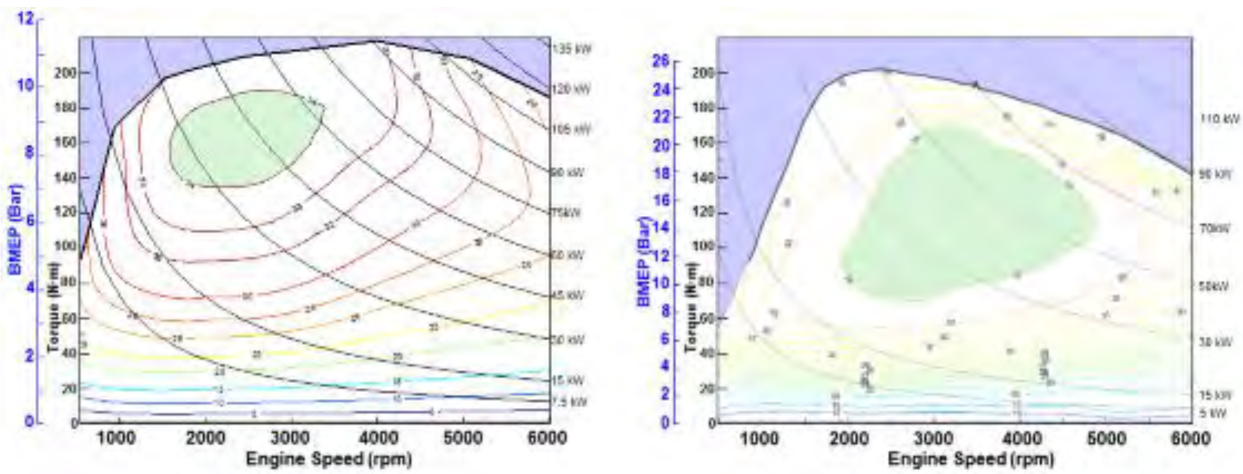


Figure 2.7 Comparison of BTE for A Representative MY2010 2.4L NA PFI Engine[K] (Left) and A Modern, 1.0L Turbocharged, Downsized GDI Engine[L] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green.

A comparison of the same 2.4L PFI engine with a more recent, MY2017 Honda L15B7 1.5L Turbocharged GDI engine with IEM is shown in Figure 2.8.[17,18] The torque characteristics of the Honda engine are a closer match to the 2.4L PFI engine and the Honda engine represents approximately 37 percent downsizing relative to the 2.4L PFI engine due to turbocharging and includes other improvements (friction reduction, dual cam phasing, higher rates of internal EGR). The Honda 1.5L turbocharged GDI engine has significantly improved efficiency when comparing BTE across 20 speed and load points of significance for the regulatory drive cycles (1500 -2500 rpm and 2-bar to 8-bar BMEP as referenced to the 2.4l ENGINE). The BTE of the Honda 1.5L turbocharged engine showed an incremental effectiveness of 6 percent to 30 percent across this entire range of operation. The difference was more pronounced at lighter loads. Incremental effectiveness was 16 percent to 30 percent below 6-bar BMEP relative to the 2.4L engine (~112 N-m of torque).

[K] Based on engine dynamometer test data provided to EPA as part of "Light Duty Vehicle Complex Systems Simulation," EPA Contract No. EP-W-07-064, work assignment 2-2, with PQA and Ricardo.
[L] Adapted from Ernst et al. 2011.[16]

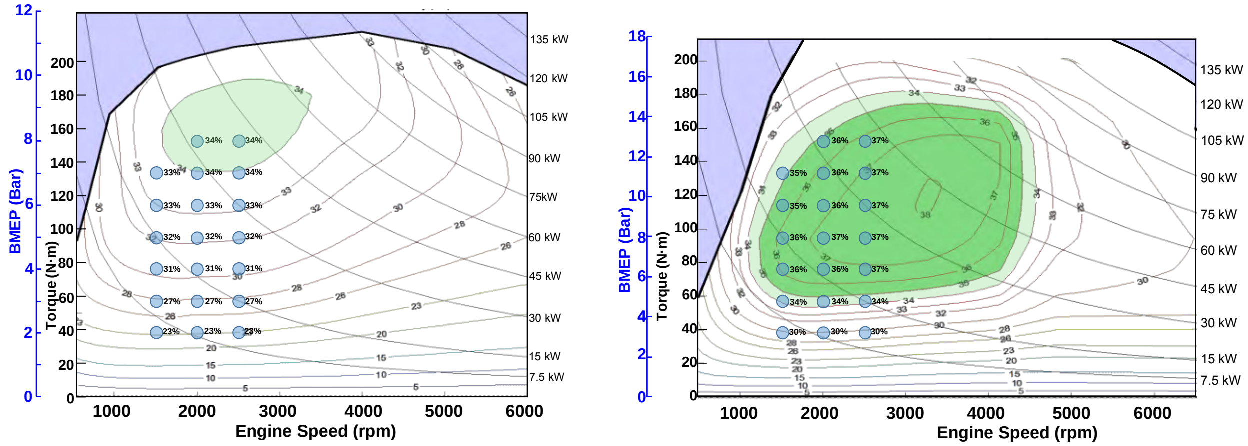


Figure 2.8 Comparison of BTE for A Representative MY2010 2.4L NA PFI Engine[K] (Left) and A Modern, 1.5L Turbocharged, Downsized GDI Engine[M] (Right).

Note: Area of Operation > 34% BTE is Shown in Light Green. Area of Operation >35% BTE is Shown in Dark Green. BTE Was Also Compared Across 20 Operational Points of Significance for Regulatory Drive Cycles between 1500 and 2500 RPM.

Recent turbocharger improvements have included use of lower-mass, lower inertia components and lower friction ball bearings to reduce turbocharger lag and enable higher peak rotational speeds. Improvements have also been made to turbocharger compressor designs to improve compressor efficiency and to expand the limits of compressor operation by improving surge characteristics (see Figure 2.9).

[M] Adapted from Wada et al. 2016 and Nakano et al 2016.[17,18]

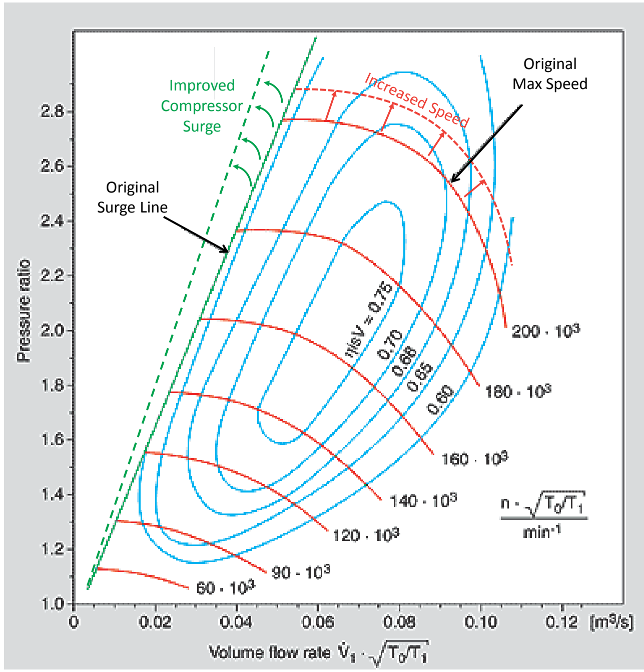


Figure 2.9 Typical Turbocharger Compressor Map Showing How Pressure And Flow Characteristics Can Be Matched Over a Broader Range of Engine Operation Via Surge Improvement and Higher Operational Speed.

Turbochargers with variable nozzle turbines (VNT) use moveable vanes within the turbocharger to allow adjustment of the effective exhaust turbine aspect ratio, allowing the operation of the turbocharger to be better matched across the entire speed and load range of an engine. VNT turbochargers are commonly used in modern light-duty and heavy-duty diesel engines. The use of head-integrated exhaust manifolds (IEM) and split-coolant loops within the engine and the use of cooled EGR (Chapters 2.2.2.8 and 2.2.2.11) can reduce peak exhaust temperatures sufficiently to allow lower cost implementation of VNT turbochargers in spark ignition engines. There are also synergies between the application of VNT and Miller cycle (increased low-speed torque, improved torque response).[13]

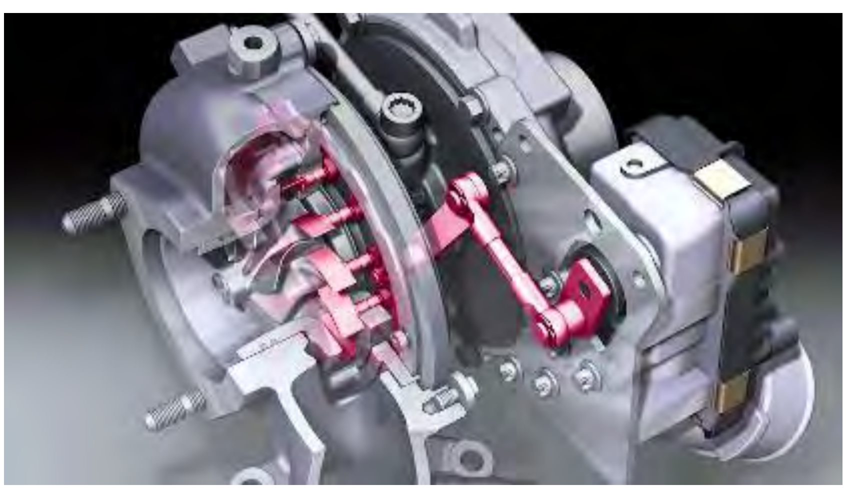


Figure 2.10 Cross Sectional View of a Honeywell VNT Turbocharger

Note: The moveable turbine vanes and servo linkage are highlighted in red.

2.2.2.8 EGR

Exhaust gas recirculation (EGR) is a broad term used for systems that control and vary the amount of inert, residual exhaust gases left in cylinder during combustion. EGR can improve efficiency at part-load by reducing pumping losses due to engine throttling. EGR also reduces combustion temperatures and thus reduces NOx formation. The use of cooled EGR can reduce knocking combustion, thus allowing compression ratio and/or turbocharger boost pressure to be increased or spark timing to be advanced. EGR also slows the rate of combustion, so its use is often accompanied by other changes to the engine (e.g., inducing charge motion and turbulent combustion) to shorten combustion duration and allow improved combustion phasing. Internal EGR uses changes in independent cam-phasing to vary the overlap between intake and exhaust valve timing events, thus changing the amount of residual gases trapped in cylinder after cylinder scavenging. External EGR recirculates exhaust gases downstream of the exhaust valve back into the air induction system. With turbocharged engines, there are variants of external EGR that use a low pressure loop, a high pressure loop or combinations of the two system types (see Figure 2.11). External EGR systems can also incorporate a heat-exchanger to lower the temperature of the recirculated exhaust gases (e.g., cooled EGR or cEGR), improving both volumetric efficiency and enabling higher rates of EGR. Nearly all light-duty diesel engines are equipped with cEGR as part of their NOx emission control system. Some diesel applications also use relatively large amounts (>25 percent) of cEGR at light- to part-load conditions to enable dilute low-temperature combustion (see Chapter 2.2.2.11 for a more detailed description of light-duty diesel technologies). Research is also underway to apply similar forms of low-temperature combustion using high EGR rates to gasoline engine applications. This includes lean-homogenous compression auto ignition (see Chapter 2.2.2.14) and other homogenous charge compression ignition concepts (see Chapter 2.2.2.11).

The use of cEGR was analyzed as part of EPA's technology packages for post-2017 light-duty vehicles with engines at 24-bar BMEP, primarily as a means to prevent pre-ignition at the high turbocharger boost levels needed at 24-bar BMEP and above. The analysis did take into account efficiency benefits from the use of cEGR with turbocharged engines due primarily to part-load reductions in pumping losses and the reduction or elimination of commanded fuel enrichment under high-load conditions.

Prior to 2012, there were no examples of production vehicles equipped with turbocharged GDI engines using cEGR. The PSA 1.2L EB PureTech Turbo engine was recently launched in the MY2014 Peugeot 308 in Europe as the first high-volume production application of cEGR on a turbocharged GDI engine. This engine has over 24-bar BMEP and also operates using Miller Cycle (see Chapter 2.2.2.10 for a more detailed description of Miller-Cycle). The MY2016 Mazda CX-9 2.5L SKYACTIV Turbo engine similarly combines the use of Miller Cycle with cEGR.

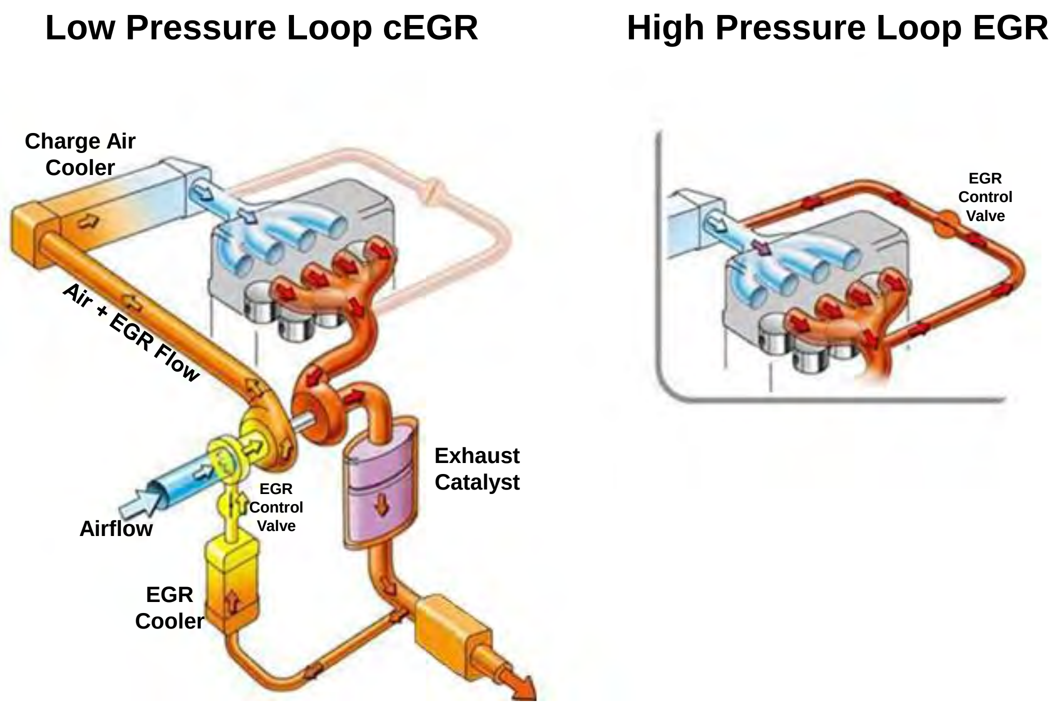


Figure 2.11 A Functional Schematic Example of a Turbocharged Engine Using Two Variants of External EGR.

Note: The Schematic On The Left Shows The Details Of A Low Pressure Loop (Post-Turbine To Pre-Compressor) CEGR System. The Schematic Inset on the Right Shows High Pressure Loop (Pre-Turbine to Post-Compressor) EGR.[19] In The FRM Analysis, Some TDS24 Packages And All TDS27 Packages Used Dual-Loop (Both High And Low Pressure) EGR.

2.2.2.9 Atkinson Cycle

Typical 4-cycle internal combustion engines have an effective compression ratio and effective expansion ratio that are approximately equivalent. Current and past production Atkinson Cycle engines use changes in valve timing (e.g., late-intake-valve-closing or LIVC) to reduce the effective compression ratio while maintaining the expansion ratio (see Figure 2.12 and Figure 2.13). This approach allows a reduction in top-dead-center (TDC) clearance ratio (e.g., increase in “geometric” or “physical” compression ratio) to increase the effective expansion ratio without increasing the effective compression ratio to a point that knock-limited operation is encountered. Increasing the expansion ratio in this manner improves thermal efficiency but also lowers peak brake-mean-effective-pressure (BMEP), particularly at lower engine speeds.[N] Depending on how it is implemented, some Atkinson Cycle engines may also have sufficient cam-phasing authority to widely vary effective compression ratio and can use this variation as a means of load

[N] BMEP is defined as torque normalized by cylinder displacement. It allows for emissions and efficiency comparisons between engines of different displacement.

control without use of the standard throttle in some operating conditions, resulting in additional pumping loss reductions.

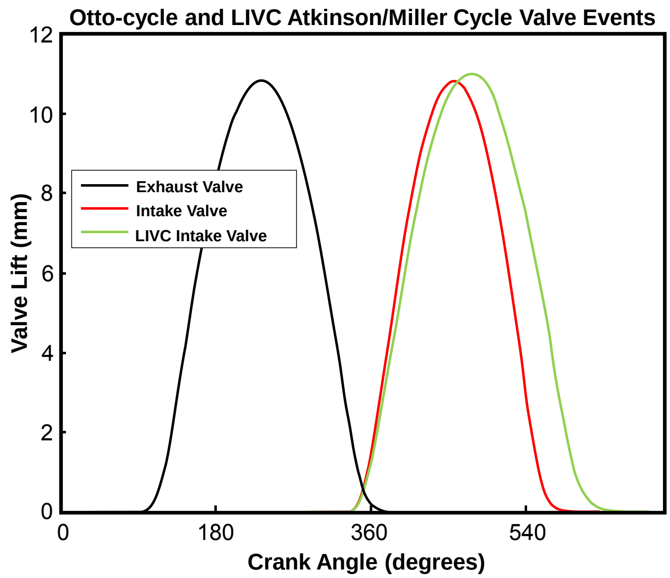


Figure 2.12 Comparison of the Timing of Valve Events for Otto-Cycle (black and orange lines) and LIVC Implementations of Atkinson- Or Miller-Cycle (black and green lines).

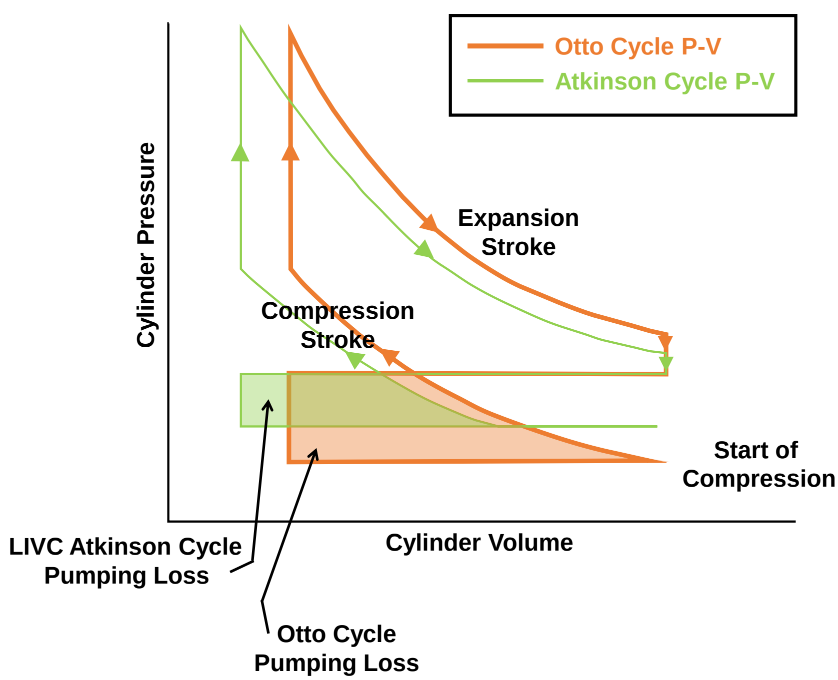


Figure 2.13 Diagrams of Cylinder Pressure Vs. Cylinder Volume For a Conventional Otto-Cycle SI Engine (orange line) Compared to a LIVC Implementation of Atkinson Cycle (green line) Highlighting the Reduction in Pumping Losses.

Prior to 2012, the use of naturally-aspirated Atkinson Cycle engines has been limited to HEV and PHEV applications where the electric machine could be used to boost torque output, particularly at low engine speeds. Because of this, EPA's analyses for the FRM did not include the use of Atkinson Cycle outside of HEV and PHEV applications. Nearly all HEV/PHEV applications in the U.S. use Atkinson Cycle, including the Honda Insight, Toyota Prius, Toyota Camry Hybrid, Lexus 400h, Hyundai Sonata Hybrid and Chevrolet Volt. The Toyota 2ZR-FXE used in the third-generation Toyota Prius and Lexus 200h uses a combination of LIVC Atkinson Cycle, cooled EGR, and port-fuel-injection (PFI) to achieve a peak BTE of 38.5 percent, the highest BTE achieved to date for a production spark-ignition engine. Further refinements to this engine, including increased tumble to increase both the speed of combustion and EGR tolerance, have resulted in peak BTE of 40 percent.[20]

Since 2012, Atkinson Cycle engines have been introduced into non-hybrid applications. These applications use camshaft-phasing with a high degree of authority together with either GDI (e.g., Mazda SKYACTIV-G 1.5L, 2.0L and 2.5L engines, Toyota 2GR-FKS engine), PFI (MY2017 Hyundai Elantra "Nu" 2.0-liter PFI Atkinson) or a combination of PFI with cooled EGR (Toyota 1NR-FKE and 2NR-FKE engines). As of MY2017, all of Mazda's engines for the U.S. market are either Atkinson Cycle or Miller Cycle (boosted Atkinson). Toyota's 2GR-FKS engine became an optional engine offered in the Toyota Tacoma pickup truck beginning in MY2016. The Tacoma is currently the mid-size pickup truck segment sales leader in the U.S. The Toyota Tacoma equipped with the 2GR-FKS Atkinson Cycle engine has an SAE J2807 tow rating of 6,800 pounds. The Hyundai "Nu" 2.0-liter PFI Atkinson Cycle engine is the base engine offering in the Hyundai Elantra. The Hyundai Elantra is currently within the top 5 in sales within the compact car segment in the U.S.

The effective compression ratio of Atkinson Cycle engines can be varied using camshaft phasing to increase BMEP and GDI (Mazda) or cEGR (Toyota) are used, in part, for knock mitigation. These engines from Mazda and Toyota also incorporate other improvements, such as friction reduction from valvetrain and piston design enhancements. The Toyota 1NR-FKE 1.3L I3 and 2NR-FKE 1.5L I4 engines achieve a peak BTE of 38 percent, very close to the BTE achieved with the 2ZR-FXE engine used in the Toyota Prius.[20,21] EPA testing of 2.0L and 2.5L variants of the Mazda SKYACTIV-G engine achieved peak BTE of 37 percent while using either 88AKI (91 RON) or 92 AKI (96 RON) fuel. More important from a standpoint of drive-cycle fuel economy and CO_2 emissions was the very large "island" of more than 32 percent BTE (Figure 2.14) which, depending on the transmission and road load, would cover most operation over the UDDS and HWFET regulatory drive cycles depending on the specific vehicle application (e.g., road loads, final drive, gear-ratio spread). In the case of the Mazda SKYACTIV-G engines, the use of GDI and cam-phasing resulted in increased BMEP and rated power relative to the previous PFI, non-Atkinson versions of this engine and allowed a small degree of engine downsizing (e.g., replacement of the previous 2.5L PFI engine with the 2.0 SKYACTIV-G) on some Mazda platforms with equal or improved performance. In the case of the Toyota 1NR-FKE, the use of cEGR and cam-phasing allowed BMEP to be maintained relative to peak BMEP of the Non-Atkinson Cycle engine it replaced and allowed the use of a lower cost PFI fuel system. Both the Mazda and Toyota Atkinson Cycle engines use electro-mechanical systems for camshaft phasing on the intake camshaft.

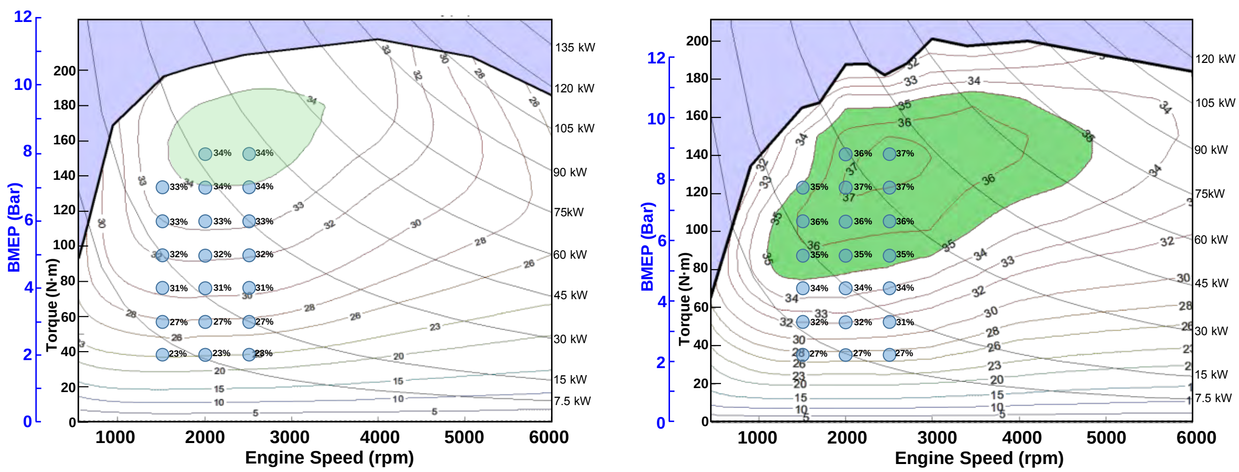


Figure 2.14 Comparison of BTE for a Representative MY2010 2.4L NA PFI Engine[O] (left) and a 2.0L NA GDI LIVC Atkinson Cycle Engine (right) tested by EPA.[P,22]

A recent benchmarking analysis by EPA of a 2014 Mazda SKYACTIV-G naturally aspirated (NA) gasoline direct injection (GDI) engine showed a peak BTE of approximately 37 percent, relatively high for SI engines.[P,23] This was in part due to an ability to use late-intake-valve-closing (LIVC) Atkinson-cycle operation to decouple the knock-limited effective CR from the expansion ratio available from a very high 13:1 geometric CR. This can be seen in the variation of effective compression ratio observed during dynamometer testing, where the maximum effective CR (~11 to 11.5:1) is comparable to other GDI naturally aspirated GDI engines having 87 AKI gasoline as a recommended fuel, for example 2015 and later GM Ecotec3 V6 and V8 engines (see Figure 2.15).

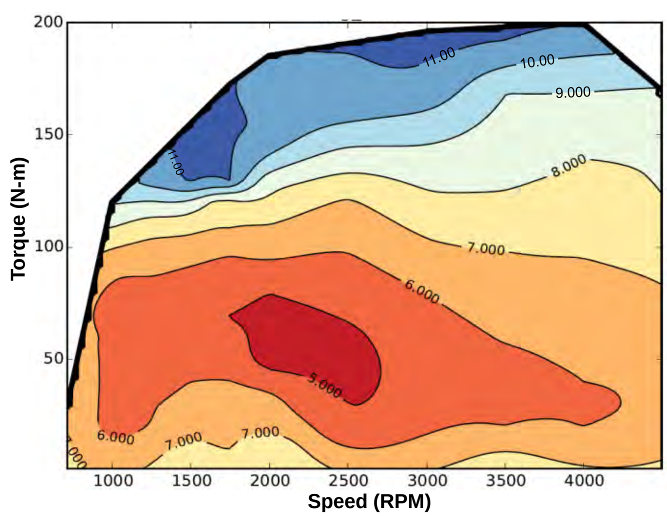


Figure 2.15 Measured effective compression ratio for 2.0L NA GDI LIVC Atkinson Cycle Engine (right) tested by EPA.

[O] Based upon engine dynamometer data provided to EPA under a contract with PQA and Ricardo, "Light Duty Vehicle Complex Systems Simulation" EPA Contract No. EP-W-07-064, work assignment 2-2.

[P] Derived from EPA engine dynamometer data first presented by Lee et al. 2016. [22]

Note that the thick black line denotes measurement and calculation limits for mapping and does not necessarily reflect maximum rated torque at each speed condition.

The Mazda SKYACTIV-G is one of the first implementations of a naturally-aspirated, LIVC Atkinson-cycle engine in U.S. automotive applications outside of hybrid electric vehicles (HEV) and also appears to be the first Atkinson-cycle engine to use GDI. Port-fuel-injected (PFI) Atkinson-cycle engines have been used in hybrid electric vehicle applications in the U.S. for over a decade. PFI/Atkinson-cycle engines have demonstrated peak BTE of approximately 39 percent in the 2015 Honda Accord HEV and 40 percent in the 2016 Toyota Prius HEV. Atkinson-cycle engines can achieve comparable or better peak BTE in comparison with downsized, highly boosted, turbocharged GDI engines like the Ricardo EGRB configuration analyzed within the FRM. However, such modern turbocharged GDI engines often have relatively high BTE across a broader range of engine speed and torque as well as improved BTE and fuel consumption at light loads compared with Atkinson-cycle engines, as shown in Figure 2.16. Based on EPA's initial engineering analysis of the Mazda SKYACTIV-G engine, it appeared that another reasonable, alternative technological path to both high peak BTE and a broad range of operation with high BTE might be possible through the application of cooled-EGR (cEGR), a higher compression ratio, and cylinder deactivation to a naturally-aspirated GDI/Atkinson-cycle engine like the SKYACTIV-G. Discussion of modeling and engine development by EPA of application of these technologies to an Atkinson-cycle engine are summarized in Chapter 2.3 of the TSD.

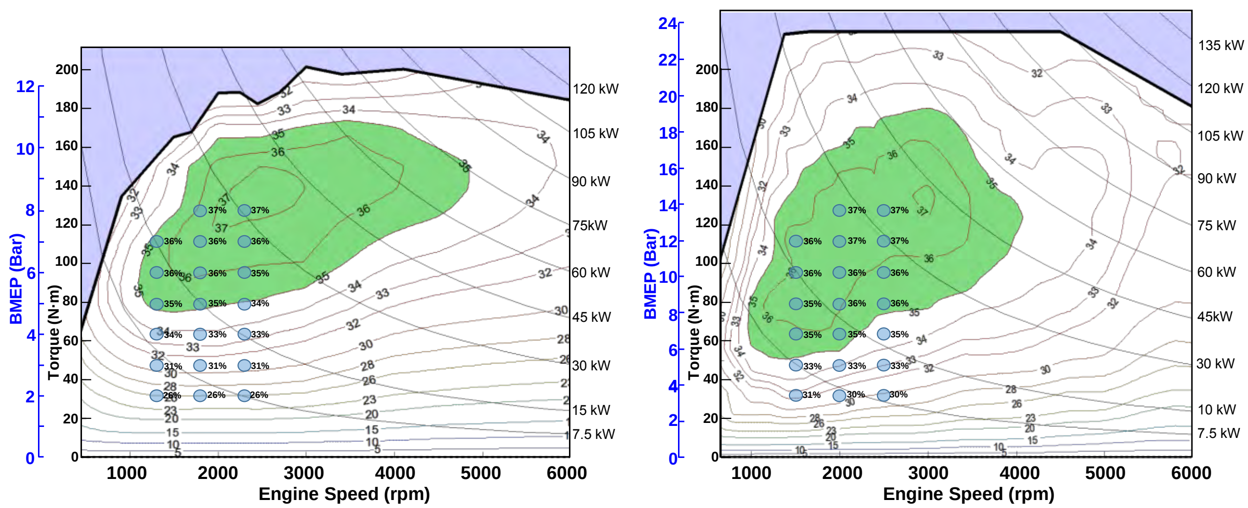


Figure 2.16 A Comparison of BSFC Maps Measured For The 2.0L 13:1CR SKYACTIV-G Engine[P] (left) and Modeled For A 1.0L Ricardo "EGRB Configuration"[O] (right).

2.2.2.10 Miller Cycle

Like Atkinson Cycle, Miller Cycle engines use changes in valve timing to reduce the effective compression ratio while maintaining the expansion ratio. Automakers have investigated both early intake valve closing (EIVC) and LIVC variants. There is some disagreement over the application of the terms Atkinson or Miller Cycle to EIVC and LIVC valve event timing and sometimes the terms are used interchangeably. For the purpose of EPA's analyses, Miller Cycle is a variant of Atkinson cycle with intake manifold pressure boosted by a either a turbocharger and/or a mechanically or electrically driven supercharger. It is simply an extension of Atkinson Cycle to boosted engines and can use either EIVC or LIVC. The first production vehicle offered using Miller Cycle was the MY1995 Mazda Millenia S, which used the KJ-ZEM 2.3L PFI engine with a crankshaft-driven Lysholm compressor for supercharging. Until recently, no Miller Cycle gasoline SI engines were in mass production after 2003, and Miller Cycle was not evaluated as a potential gasoline engine technology as part of the 2017-2025 GHG FRM.

As with Atkinson Cycle engines, the use of GDI and camshaft-phasing with a high degree of authority have significant synergies with Miller Cycle. Modern turbocharger and charge air cooling systems allow Miller Cycle engines to attain BMEP levels approaching those of other modern, downsized, turbocharged GDI engines. The 1.2L I3 PSA "EB PureTech Turbo" Miller engine launched in Europe, N. Africa and S. America in the MY2014 Peugeot 308[24]. In addition to Miller Cycle, the engine also uses cEGR. This engine has a maximum BMEP of 24-bar and is similar in many respects to the Ford 1.0L I3 EcoBoost but achieves 35 percent BTE over a slightly broader area of operation vs. 34 percent BTE for the EcoBoost (see Figure 2.17).

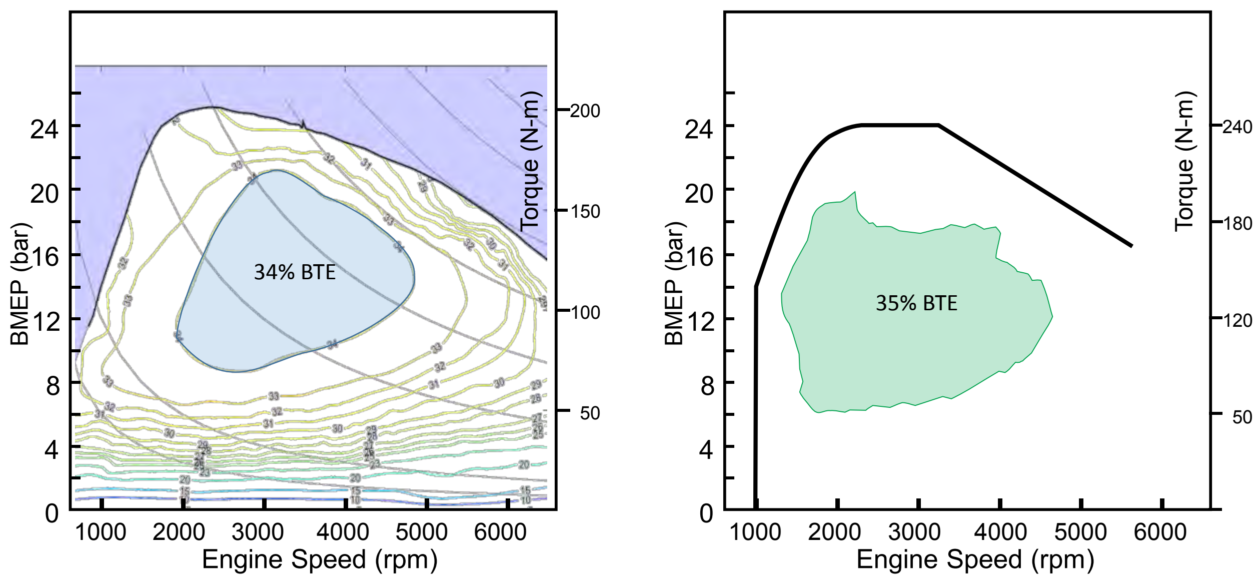


Figure 2.17 Comparison of BTE for Downsized, Turbocharged GDI Engines.

Note: Ford 1.0L EcoBoost Engine Is On The Left And A 1.2L Miller Cycle PSA EB Puretech Engine Is On The Right. A More Detailed BTE Map Is Not Yet Available For The PSA Engine.

In MY2017, VW will be launching a Miller Cycle variant of the 2.0L EA888 turbocharged GDI engine in the U.S. The VW implementation of Miller Cycle has a second Miller Cycle cam profile and uses camshaft lobe switching on the intake cam to go into and out of an EIVC implementation of Miller Cycle.[25,26] The peak BTE of 37 percent is higher than that of the PSA Miller cycle engine, in part due to a higher expansion ratio (geometric CR of 11.7:1 for the VW engine vs. 10.5:1 for the PSA engine). Like the PSA engine, the VW uses high-pressure cEGR. Peak BTE is comparable to the Mazda SKYACTIV-G engines but is available over a broader range of speed and load conditions. Both Atkinson and Miller Cycle engines show broad areas of operation at greater than 32 percent BTE. Figure 2.18 shows a comparison between a

MY2010 3.5L NA PFI DOHC V6 and the VW 2.0L EA888 Miller Cycle engine with comparable torque delivery. The area of operation at greater than 32 percent BTE is approximately double for the Miller Cycle engine relative to the DOHC PFI engine. BTE is improved by approximately 40 percent at light load for the Miller Cycle engine and peak BTE is improved approximately 6 percent. Mazda recently introduced a 2.0L Miller Cycle engine with cEGR and a unique exhaust scavenging system in the 2016 CX9 SUV.[27]

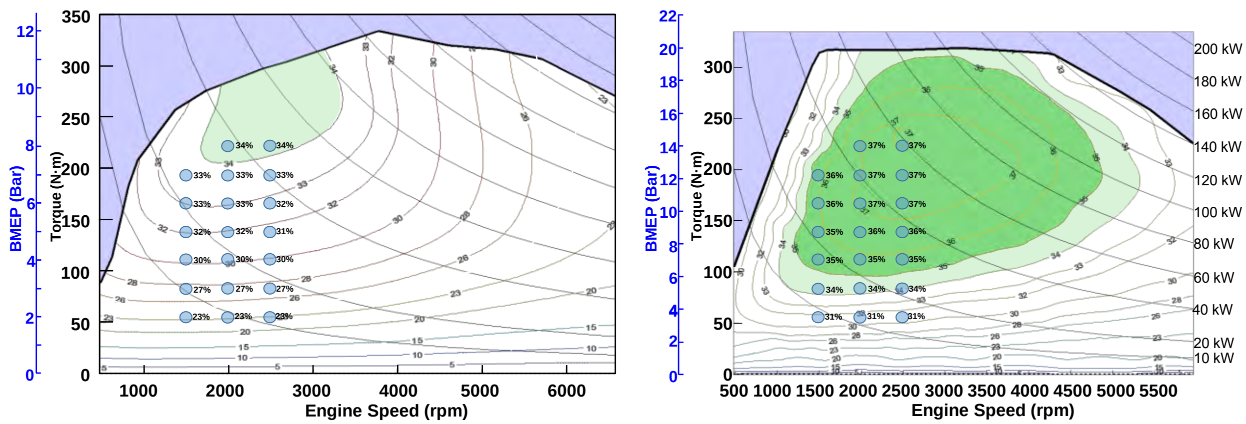


Figure 2.18 Comparison of BTE for A Representative MY2010 3.5L NA PFI V6 Engine[Q] (Left) And A Downsized 2.0L I4 Miller Cycle Engine[R] (Right).

Note: The Light Green Area Shows Regions of >34% BTE. The Dark Green Area Shows a Region >35% BTE.

Since VW has published detailed data for both Miller Cycle and a turbocharged GDI (non-Miller) variants of the EA888 series of engines, a more direct comparison between turbocharged, downsized GDI and Miller Cycle engines is possible. Figure 2.19 shows BTE for both variants of the 2.0L I4 VW EA888 engine. When comparing BTE at comparable BMEP, there is a 6-10 percent incremental improvement for the Miller Cycle engine relative to the turbocharged GDI engine over a broad area of operation from 1500-2500 rpm and from 2-bar to 12-bar BMEP (i.e., below 55 - 60 percent of peak BMEP - areas of importance for the regulatory drive cycles).[S] Comparing BTE of the 2.0 Miller cycle variant to the smaller displacement, 1.8L version of the same engine family (similar 22-bar BMEP to the 2.0L turbocharged GDI, but equivalent torque to the 2.0L Miller Cycle engine) lowers the incremental effectiveness for Miller Cycle to approximately 4-7 percent relative to a turbocharged GDI engine and comparable partial load operation from 1500-2500 rpm. Confidential business information from a Tier 1 automotive supplier provided an estimate of approximately 5 percent CO_2 combined-cycle incremental

[Q] Based upon engine dynamometer data provided to EPA under a contract with PQA and Ricardo, "Light Duty Vehicle Complex Systems Simulation" EPA Contract No. EP-W-07-064, work assignment 2-2.

[R] Adapted from Wurms et al. 2015.**Error! Bookmark not defined.**

[S] Note that VW did not significantly change the turbocharging system when applying Miller Cycle to this engine family, so the Miller Cycle variant has a peak BMEP of 20-bar instead of 22-bar due to the reduced volumetric efficiency from EIVC. Turbocharger improvements (e.g., higher pressure ratio and different flow characteristics) would be necessary to maintain the 2.0L Miller Cycle engine at 22-bar BMEP, thus comparisons in this case are limited to 20-bar BMEP and below.

benefit for Miller Cycle relative to a 24-bar BMEP turbocharged, downsized engine and a loss of approximately 8-12 percent peak BMEP due to reduced volumetric efficiency for Miller Cycle. This is consistent relative to the data published by VW. There may also be synergies between Miller Cycle and CDA. A comparison Miller and non-Miller variants of the VW EA211 TSI turbocharged engine, both with CDA, shows a relative effectiveness of 5-30 percent for the Miller Cycle variant of the engine over regions of operation that are important for U.S. regulatory drive cycles.[13] The Miller Cycle variant of the VW EA211 TSI has a geometric CR of 12.5:1 and uses a VNT turbocharger.

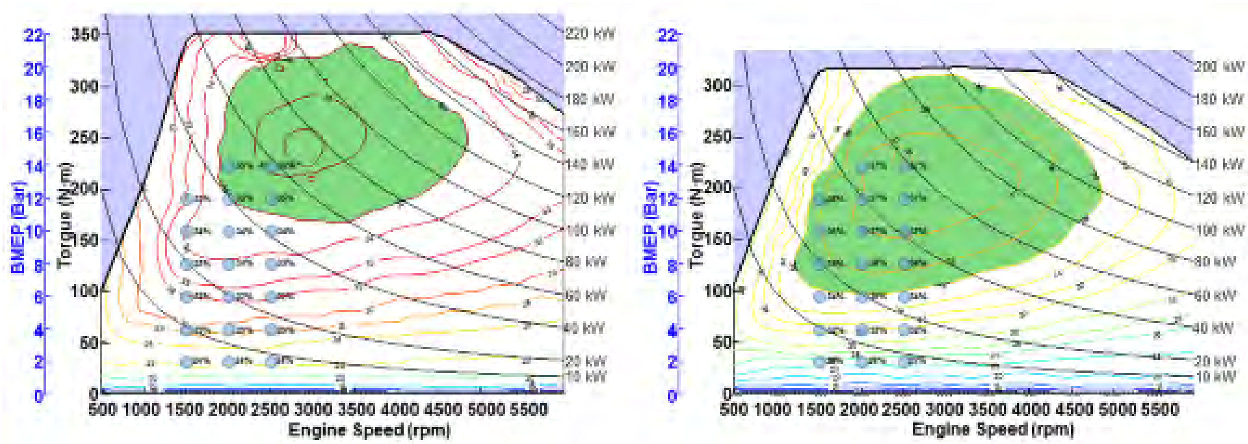


Figure 2.19 Comparison of BTE for 2015 Turbocharged, Downsized GDI (left) and 2017 Miller Cycle (right) variants of the same engine family, the 2.0L VW EA888.[R]

Note: Green area shows region of high (35%) BTE.

2.2.2.11 Light-duty Diesel Engines

Diesel engines have characteristics that differ from gasoline spark ignition (SI) engines and allow improved fuel efficiency, particularly at part-load conditions. These include reduced pumping losses due to lack of (or greatly reduced) throttling, and a combustion cycle that operates at a higher compression ratio and at very lean air/fuel ratio when compared with an equivalent-performance gasoline engine. Operating with a lean-of-stoichiometric air/fuel ratio poses challenges with respect to NOx control, requiring either a NOx adsorption catalyst (NAC), urea or ammonia-based selective catalytic reduction (SCR) or some combination of NAC and SCR in order to meet Federal Tier 3 and California LEV III NOx emissions standards. Beginning with Federal Tier 2 emission standards. It has also been necessary to equip light-duty diesels with catalyzed diesel particulate filters (CDPFs) in order to comply with light duty PM emission standards.

Detailed analysis of the vehicle simulation results used within the FRM uncovered some shortcomings within the MSC EASY5 vehicle simulations used as light-duty diesel vehicle GHG effectiveness inputs into the Ricardo Surface Response Model. The modeled light-duty diesel technology packages did not operate in the most efficient regions of engine operation. This may have been in part due to inconsistencies in the application of the optimized shift strategy and in part due to an oversight that resulted in the apparent oversizing of light-duty diesel engine displacements. For example, plotting the average engine speed and load operating points over the regulatory drive cycles for the MSC EASY5 diesel simulations on top of the diesel engine maps showed that there was significant potential for improvement in the choice of selected gear. As a result, additional analyses using the ALPHA vehicle simulation model have been conducted for light-duty diesel engine technology packages in order to update GHG effectiveness from these packages.

Light-duty diesel engines have also evolved considerably over the last five years, particularly in Europe. Modern light-duty diesel engine designs appear to be following similar trends to those of turbocharged GDI engines and, in some cases, heavy-duty diesel engine designs, including:

- Engine downsizing (increased peak BMEP)
- Engine down-speeding
- Advanced friction reduction measures
- Reduced parasitics
- Improved thermal management
- Use of a combination of both low- and high-pressure-loop cooled EGR
- Advanced turbocharging, including the use of VNT and sequential turbocharging
- Incorporation of highly-integrated exhaust catalyst systems with high NOx and PM removal efficiencies
- Adoption of high-pressure common rail fuel injection systems with higher injection pressures and increased capability (i.e., multiple injections per firing cycle)

The highest BMEP engines currently in mass-production for high-volume light-duty vehicle applications are all diesel engines. MY2016-2017 light-duty diesel engines are available from Honda, BMW and Mercedes Benz in the EU with approximately 26-bar to 29-bar BMEP and peak cylinder pressures at or above 200-bar. [28,29,30] The light-duty diesel technology packages used in the FRM analyses relied on engine data with peak BMEP in the range of 18 - 20 bar. These were engine configurations using single-stage turbocharging with electronic wastegate control, high-pressure or low-pressure (single-loop) cooled EGR, and common-rail fuel injection with an 1800 bar peak pressure. The cost analysis in the FRM for advanced light-duty diesel vehicles assumed use of using a DOC+DPF+SCR system for meeting emissions standards for criteria pollutants.

In response to EPA Heavy Duty GHG emissions standards, large Class 8 heavy-duty truck engine designs have exceeded 50 percent BTE.[31,32] Despite their inherent differences, there now appears to be a significant transfer of technology from heavy-duty diesel engines to much smaller bore, higher speed light-duty diesel engines underway, particularly for engines with high BMEP. Use of CAE tools to design complex, stepped-geometry steel piston crowns and the use of carefully designed piston oil-cooling galleries result in remarkably similar approaches when comparing recent approaches to heavy-duty truck piston designs to recent light-duty diesel engine piston designs such as that of the Mercedes-Benz OM654.[31,33] The Mercedes-Benz OM654 engine incorporates other design elements that are similar to current heavy-duty diesel engine designs, including driving the camshaft and some auxiliaries off of the rear of the engine, the use of a high pressure common rail (HPCR) fuel injection systems with 2050 bar peak pressure and the use of a VNT turbocharger. BMW's B57 light-duty diesel engine used in the MY2017 BMW 730d and 740d uses an HPCR fuel injection system currently with 2500 bar peak pressure and with capability to expand peak pressures to 3000 bar. Driving injection pressures higher allows more flexibility for use of multiple injections and allows better optimization of combustion phasing. Modern, high BMEP light-duty diesel engines using conventional diffusional combustion are capable of peak BTE of approximately 42 percent (see Figure 2.20).[34]

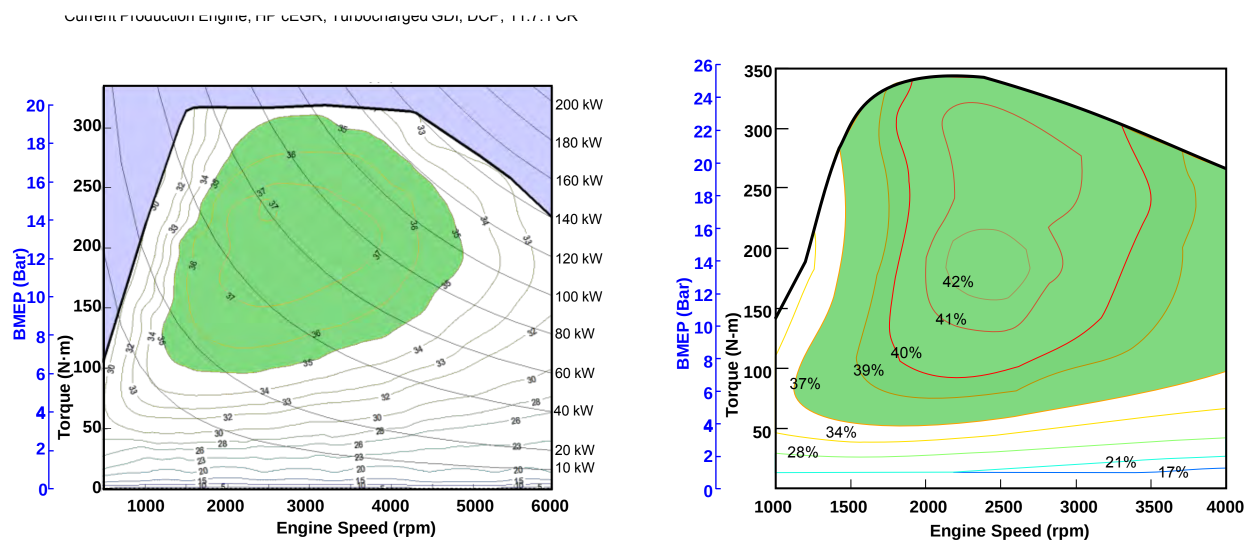


Figure 2.20 Comparison Of BTE For A Downsized SI 2.0L I4 Miller Cycle Engine (Left)[T] And A 1.7L I4 Turbocharged Diesel Engine With HPCR, Low And High Pressure Loop CEGR, And VNT Turbocharger (Right).[U]

Note: Green area shows region of high (35%) BTE.

Advanced turbocharging and cooled EGR systems allow higher rates of EGR to be driven and, when combined with more capable, higher pressure (2000-3000 bar) HPCR systems can allow a degree of operation at light loads using pre-mixed charge compression ignition (PCCI) or other low-temperature modes of combustion with inherently low NOx and PM emissions and reduced thermal losses over a broader area of engine operation. Cummins "Light-duty Efficient, Clean Combustion" engine development program for the U.S. DOE used mixed-mode, part-load PCCI/high-load diffusional combustion approach and achieved a 20 percent improvement in uncorrected city-cycle fuel economy (e.g., from 20.3 mpg to 24.5 mpg) when compared to a more conventional diesel in a 5000 lb. inertial test weight SUV at Tier 2, Bin 5 emissions levels. Peak BTE for the PCCI combustion mode was approximately 46 percent compared with 42 percent peak BTE for conventional diffusional diesel combustion. Cummins developed a similar dual-mode combustion approach as part of the Advanced Technology Powertrains for Light-Duty (ATP-LD) and the Advanced Technology Light Automotive Systems (ATLAS) engine development programs for the U.S. DOE.[35,36] The engines developed as part of this program combined dual-mode PCCI/diffusional combustion together with further improvements to the turbocharger and charge air cooler systems, improved integration of the catalytic CDPF and urea-SCR systems and addition of a NAC system for storage of cold-start NOx emissions. Developmental engines and emissions control systems were integrated into Nissan Titan full-size

[T] Adapted from Wurms et al. 2015.
[U] Adapted From Busch Et Al. 2015.[34]

2-wheel-drive pickup trucks and achieved emissions consistent with Tier 3 Bin 30 compliance and 21.8/34.3/26.0 City/Highway/Combined (uncorrected) fuel economy at a 5500 lb. inertial test weight. A similar engine used in the mid-size Nissan Frontier 4-wheel drive pickup at reduced peak BMEP (21.3 bar vs. 23.4 bar in the Titan demonstration) achieved a 35 percent combined cycle fuel economy improvement relative to the MY2015 4.0L PFI V6 Nissan Frontier.[37]

2.2.2.12 Thermal Management

Most recent turbocharged engine designs now use head-integrated, water-cooled exhaust manifolds and coolant loops that separate the cooling circuits between the engine block and the head/exhaust manifold(s) (Figure 2.21). Examples include the head-integrated exhaust manifolds (IEM) and split-coolant loops used with the Ford 1.0L I3, 1.5L I4, 2.0L I4 and 2.7L V6 EcoBoost engines, the 2.0L VW EA888 engine, the GM EcoTec SGE 1.0L 3-cylinder and 1.4L 4 cylinder engines, and the PSA 1.2L EB PureTech Turbo. The use of IEM and split-coolant-loops is now also migrating to some naturally aspirated GDI and PFI engines, including the GM 3.6L V6 LFX and EcoTec 1.5L engines and the 1.0L 3-cylinder Toyota 1KR-FE ESTEC. These types of thermal management systems were included in the FRM analysis of turbocharged GDI engines at BMEP levels of 24-bar and above but were not considered for turbocharged engines at lower BMEP levels or for naturally aspirated engines. Benefits include:

- Improved under-hood thermal management (reduced radiant heat-load)
- Reduced thermal gradients across the cylinder head
- Reduction in combustion chamber hot spots that can serve as pre-ignition sources
- Improved knock limited operation
- Reduce or eliminate enrichment required for component protection, particularly at low-speed/high-load conditions
    - Enable additional engine "down-speeding" without encountering enrichment
- Improved control of turbine inlet temperature (turbocharged engines only)
    - Enable use of lower-cost materials turbine and turbine housing materials
    - Enable use of variable-geometry turbines similar to light-duty diesel applications
- Improved catalyst durability
- Shorter time to catalyst light-off after cold-start
- Improved coolant warmup after cold start
- Reduced noise
- Lower cost and parts count
    - Improved durability (fewer gaskets to fail)
- Reduced weight (savings of approximately 1 kg/cylinder)

Figure 2.21 Exhaust Manifold Integrated Into a Single Casting with the Cylinder Head

2.2.2.13 Reduction of Friction and Other Mechanical Losses

In urban driving, approximately 60 percent of engine losses are due to mechanical losses, including engine friction.[38] Piston and cylinder friction from the piston rings and piston skirts account for 35 percent or more of engine friction in modern light-duty gasoline engines and approximately 50 percent of engine friction in modern light-duty diesels engines.[38,39,40] The remaining frictional losses are primarily due to crankshaft, connecting rod, valvetrain and balance shaft friction. Piston skirt friction accounts for approximately 30 percent of piston friction. Molybdenum disulfide (MoS_2) and Diamond-like carbon (DLC) piston skirt coatings have demonstrated part-load engine friction reductions of approximately 16 percent and 20 percent, respectively.[39] Improvements in cylinder bore surface treatments such as plasma coatings[29,30,41] and laser roughening[42] have also been introduced in recent engine designs to reduce engine friction and improve cylinder bore wear characteristics.

Offsetting the crankshaft from the bore centerline, sometimes referred to as a désaxé cylinder arrangement, can be used to reduce side forces on the piston and piston rings during the power stroke, reducing friction piston/liner friction and reducing component wear.[43] For example, the 2ZR-FXE engine used in the 2009-2015 Toyota Prius and the 2ZR-FE engine in the 2009-2016 Toyota Corolla have the crankshaft centerline shifted 8 mm towards the intake side of the engine to reduce friction.[44]

Schaeffler has developed roller bearings that can be applied to the first and last crankshaft main bearings without the added complexity of using built crankshafts or split main bearings to reduce crankshaft friction and increase front journal load bearing capability when used with higher power P0 mild hybrid systems. Roller bearing balance shafts for 3- and 4-cylinder engines have also been developed by Schaeffler, BMW and others that can reduce balance shaft friction by approximately 50 percent.

In addition to reducing engine mechanical losses, engine friction reduction also improves engine restart when combined with stop/start systems. Reducing engine friction can also allow additional engine downspeeding while maintaining idle and off-idle engine NVH characteristics.

Hyundai and Delphi used a MY2011 2.4L 4-cylinder GDI engine to demonstrate a combined-cycle fuel economy improvement of 4 percent by using a combination of a MoS_2 piston skirt coating, CrN physical vapor-deposition coated piston rings, low tension oil control rings and engine downspeeding.[45] They also achieved a further 2.9 percent combined-cycle fuel economy improvement through use of a 2-stage variable displacement oil pump.

2.2.2.14 Potential Longer-Term Engine Technologies

In addition to the engine technologies considered for this Proposed Determination assessment, and discussed above, there are many other engine technology development efforts underway that may be fruitful in the longer-term. While introduction of engines using these combustion concepts may occur prior to 2025, EPA does not expect significant penetration of these technologies into the light-duty vehicle fleet in the 2022 to 2025 time frame.

Homogenous charge compression ignition (HCCI), gasoline compression ignition and other dilute, low-temperature compression ignition gasoline combustion concepts are topics of considerable automotive research and development due to the potential for additional pumping loss improvements at light and partial load conditions and reduced thermal losses. Challenges remain with respect to combustion control, combustion timing, and, in some cases, compliance with Federal Tier 3 and California LEV3 NMOG+NO_X standards.

Engines using variable compression ratio (VCR) appear to be at a production-intent stage of development, but also appear to be targeted primarily towards limited production, high performance and very high BMEP (27-30 bar) applications. At lower BMEP levels, other concepts (e.g., Atkinson Cycle for NA applications, Miller Cycle for boosted applications) provide a similar means to vary effective compression ratio for knock mitigation with reduced cost and complexity with some tradeoffs with respect to volumetric efficiency.

One vehicle manufacturer recently entered production with a water injection system for knock mitigation. Injection of water and water/methanol or water/ethanol mixtures into the intake systems of turbocharged and/or mechanically supercharged engines for knock mitigation is not a new concept. Aircraft engines predating World War II and some of the first turbocharged automobile applications for the U.S. market in the 1960s used such systems for knock mitigation. Water injection systems compete with other means of knock mitigation (EGR, Atkinson Cycle, Miller Cycle, and IEM/split-cooling) that do not require fluid replenishment. Current and near term applications appear to be limited to low-volume production, high performance vehicles.

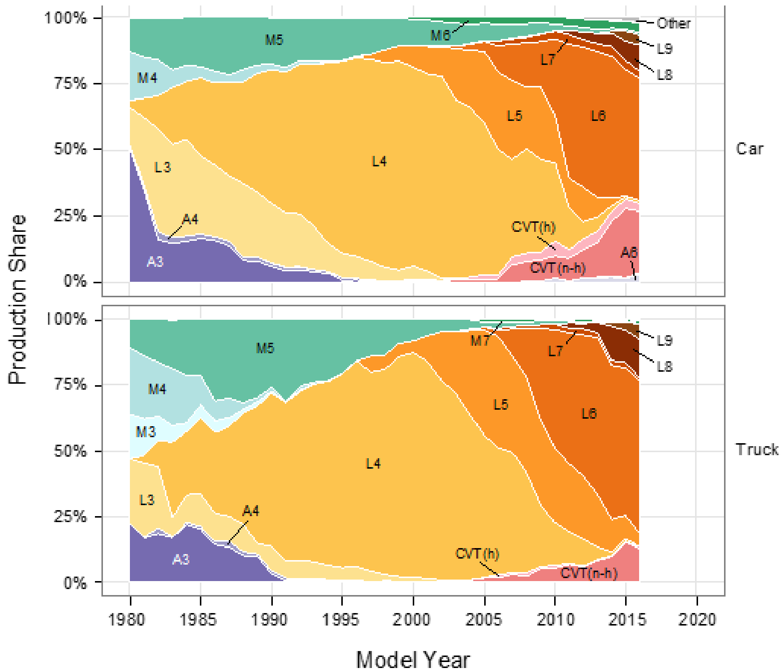
The DOE Co-Optimization of Fuels and Engines (Co-Optima) initiative aims to improve near-term efficiency of spark-ignition (SI) and compression ignition engines through the identification of fuel properties and design parameters of existing base engines that maximize performance.

According to DOE, Co-Optima is a first-of-its-kind effort brings together multiple DOE offices, national laboratories, and industry stakeholders to simultaneously conduct tandem fuel and engine R&D and deployment assessment in order to maximize energy savings and on-road vehicle performance, while also reducing long-term transportation-related petroleum consumption and GHG emissions. Two parallel research tracks focus on: 1) improving near-term efficiency of spark-ignition (SI) engines through the identification of fuel properties and design parameters of existing base engines that maximize performance. The efficiency target represents a 15 percent fuel economy improvement over state-of-the-art, future light-duty SI engines with a market introduction target of 2025; and 2) simultaneous testing of new fuels with existing CI engines (as well as advanced compression ignition [ACI] combustion technologies as they are developed) to enable a longer-term, higher-impact series of synergistic solutions. The fuel economy target represents a 20 percent improvement over state-of-the-art, future light-duty SI engines with a market introduction target of 2030. By using low-carbon fuels, such as biofuels, GHGs and petroleum consumption can be further reduced. EPA will continue to closely follow the Co-Optima program to provide input to DOE, including through EPA's technical representative on the Co-Optima External Advisory Board, as this program has the potential to provide meaningful data and ideas for GHG and fuel consumption reductions in the light-duty vehicle fleet for 2026 and beyond.

2.2.3 Transmissions: State of Technology

2.2.3.1 Background

The function of a transmission system is to reduce the relatively high engine speed and increase the torque, so that the power output of the engine can be coupled to the wheels. The complete drivetrain includes a differential (integral to the transmission on front-wheel-drive vehicles; separate on rear-wheel-drive vehicles) which provides further speed reduction, and often a hydraulic torque converter which provides significant torque multiplication at low speed conditions. The complete drivetrain – torque converter, transmission, and differential – is designed as a set to best match the power available from the engine to that required to propel the vehicle.



Transmission	Lockup?	Number of Gears	Key
Automatic Semi-Automatic Automated Manual	No	3	A3
		4	A4
		5	A5
		6	A6
		7	A7
	Yes	2	L2
		3	L3
		4	L4
		5	L5
		6	L6
		7	L7
		8	L8
		9	L9
Manual	–	3	M3
		4	M4
		5	M5
		6	M6
		7	M7
Continuously Variable (non-hybrid)	–	–	CVT(n-h)
Continuously Variable (hybrid)	–	–	CVT(h)
Other	–	–	Other

Figure 2.22 Transmission Technology Production Share, 1980 – 2015[46]

Different transmission architectures are available for use in light-duty vehicles. Conventional automatic transmissions (ATs) are the most popular type, and still dominate the light-duty fleet, as seen in Figure 2.22. Manual transmissions (MTs), although less popular than in the past, are also still part of the fleet. Both ATs and MTs have, among other improvements, seen an increase in the number of gears employed. Figure 2.22 shows the recent gains in six, seven, eight, and nine speed transmissions in both the car and light truck segment. Two other transmission types have also seen an increase in market share. These are dual-clutch transmissions (DCTs), which have significantly lower parasitic losses than ATs, and continuously variable transmissions (CVTs), which can vary their ratio to target any place within their overall spread. Each of these four types of transmissions is discussed in more detail in the sections below.

2.2.3.2 Transmissions: Summary of State of Technology

As EPA stated in the Draft TAR, in the analysis conducted for the 2012 rule, EPA estimated that DCT transmissions would be very effective in reducing fuel consumption and CO_2 emissions, less expensive than current automatic transmissions, and thus a highly likely pathway used by manufacturers to comply with the standards. This expectation was supported by comments from many OEMs at the time of the 2012 rule indicating that DCTs were part of their future compliance strategies. However, DCTs thus far, have been used in only a small portion of the fleet as some OEMs have reported in meetings with EPA. In addition, some vehicle owners have cited drivability concerns for DCT.[47] EPA also discussed in the Draft TAR that the 2017-2025MY FRM analysis also predicted a low effectiveness associated with CVTs (due to the high internal losses and small ratio spans of CVTs in the fleet at that time), and thus CVTs were not included in the FRM fleet modeling. However, internal losses in current CVTs have been much reduced and ratio spans have increased from their predecessors, leading to increased effectiveness and further adoption rates in the fleet, particularly in the smaller car segments. The new CVTs also tend to give the best effectiveness for their cost.

Again in the Draft TAR we mentioned that in the 2017-2025MY FRM, EPA estimated that step transmissions with higher numbers of gears (e.g., AT8s) would be slowly phased into the fleet. However, AT8s have been "pulled ahead," appearing in substantial numbers even before 2015MY. In addition, manufacturers have introduced nine speed transmissions and since the Draft TAR Ford has released an F150 with a 10-speed transmission. Transmissions with more than 8-speeds were not considered in the 2017-2025MY FRM.

Consistent with the Draft TAR, highlights of transmission technology analysis in this Proposed Determination include: (a) the technology packages and vehicle classes where DCTs are applicable have been re-evaluated to reflect manufacturers' current choices, (b) the effectiveness of CVTs has been re-examined and increased to reflect current vintage CVTs and their use in the fleet, and (c) nine and ten-speed transmissions were considered when determining the effectiveness of future transmissions in the fleet.

2.2.3.3 Sources of Transmission Effectiveness Data

In addition to the sources of transmission effectiveness data cited in the 2012 rule and Draft TAR, EPA also used data from a wider range of available sources to update and refine transmission effectiveness for this analysis. These sources included:

- Peer-reviewed journals, peer-reviewed technical papers, and conference proceedings presenting research and development findings
- Data obtained from transmission and vehicle testing programs, carried out at EPA-NVFEL, ANL, and other contract laboratories
- Modeling results from simulation of current and future transmission configurations
- Confidential data obtained from OEMs and suppliers on transmission efficiency

For transmission testing programs, EPA contracted with FEV Engine Technologies to test specific transmissions in a transmission component test stand. The testing program was primarily designed to determine transmission efficiency and torque loss over a range of input speeds, input loads, and temperatures. In addition, other driveline parameters, such as transmission rotational inertia and torque converter K-factor were characterized. Two automatic transmissions have been characterized in this test program, which is still on-going. Torque loss maps were generated for both a six-speed 6T40 GM automatic transmission and an eight-speed 845RE FCA automatic transmission (see Figure 2.23).

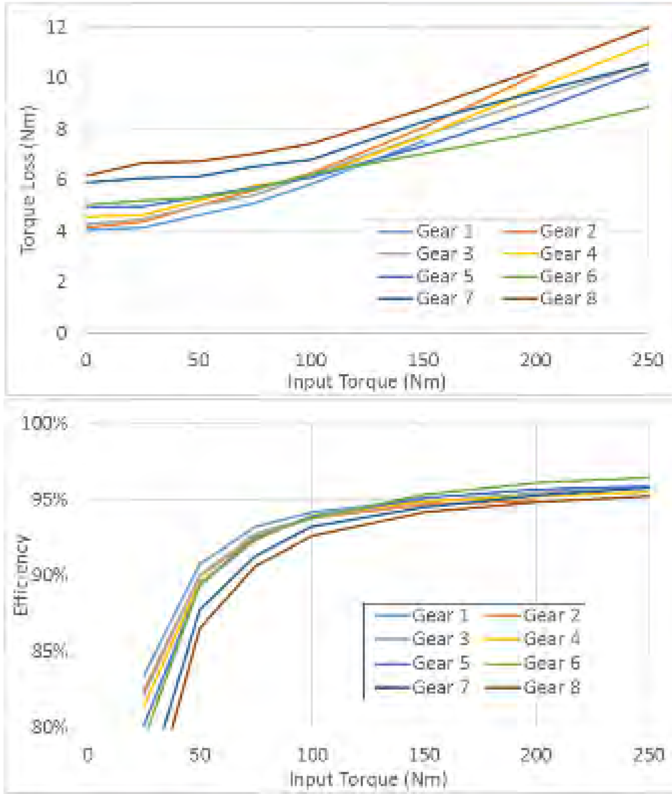


Figure 2.23 Average Torque Losses (Left) And Efficiency (Right) In Each Gear For An Eight-Speed 845RE Transmission From A Ram, Tested At 100 °C And With Line Pressures Matching Those Measured In-Use In The Vehicle. Torque Losses Were Averaged Over 1000 Rpm - 2500 Rpm. This Transmission Is A Clone of the ZF 8HP45.

In addition to contracting to test specific transmission, EPA has obtained torque loss maps and/or operational strategies for current generation transmissions from manufacturers and suppliers. These maps are CBI, but have been used to inform EPA on the effectiveness of transmissions currently on the market. Maps obtained from manufacturers and suppliers include examples of both CVTs and DCTs.

To characterize transmission and torque converter operation strategies, EPA has also performed multiple chassis dynamometer tests of current-generation vehicles equipped with a range of transmission technologies. The transmission gear and torque converter state (as well as other vehicle parameters) were recorded over the FTP, HWFET, and US06 cycles. The recorded data were used to determine the drive strategy for the engine-transmission pair in the vehicle.

The transmission losses and shifting strategy were used as modeling inputs to EPA's full-vehicle ALPHA model.[48] The shifting strategy was parameterized to allow sufficient flexibility to maintain reasonable shift strategies while changing other vehicle attributes.[49]

EPA also performed a study using chassis dynamometer testing to determine effectiveness of transmissions. In particular, two Dodge Chargers, one with a five-speed transmission and one with an eight-speed transmission, were tested on the dynamometer. Other than the transmission, these vehicles had identical powertrains, and so provided an ideal opportunity to test the effect of different transmissions in the vehicle.[50] Multiple repetitions of the FTP and HWFET, cycles were run, with the result that the Charger equipped with the eight-speed transmission exhibited on average a 6.5 percent reduction in fuel consumption over the five-speed Charger on the combined FTP/HWFET cycle. The eight-speed Charger also exhibited an increase in acceleration performance, according to tests by *Car and Driver,* with, for example, a 0.5 second improvement in 0-60 time.[51,52]

2.2.3.4 Sources of GHG Emission Improvements: Reduction in Parasitic Losses, Engine Operation, and Powertrain System Design

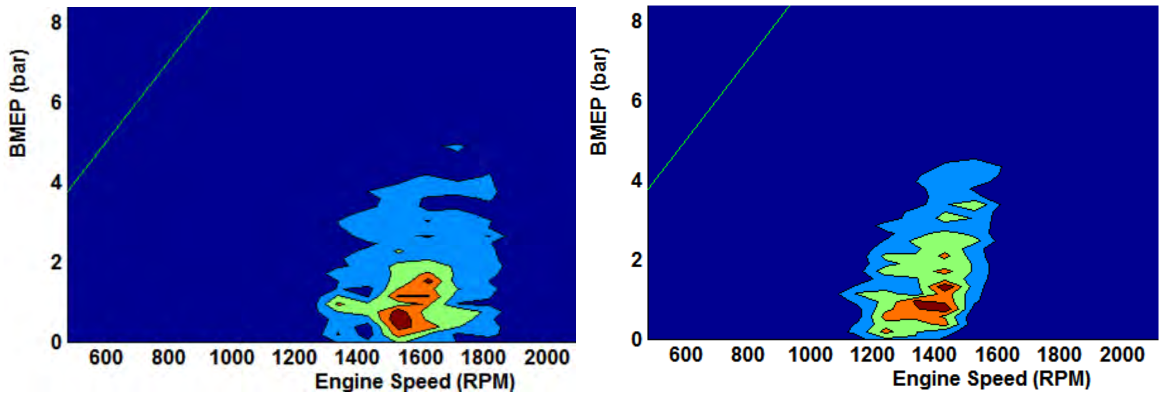
The design of the transmission system can affect vehicle GHG emissions in two ways. First, reducing the energy losses within the transmission (and/or torque converter) reduces the energy required from the engine, which also reduces GHG emissions. Reducing transmission losses can be accomplished by increasing gearing efficiency, reducing parasitic losses, altering the torque converter lockup strategy, or other means. A more in-depth discussion of internal energy loss reduction is included in the "Transmission Parasitic Losses" and "Torque Converter Losses and Lockup Strategy" sections below.

Another method to decrease GHG emissions is to design the entire powertrain system - the engine and transmission - to keep the engine operating at the highest available efficiency for as much time as possible. Transmissions with more available gears (or, at the extreme, continuously variable transmissions) can maintain engine operation within a tighter window, and thus maintain operation nearer the highest efficiency areas of the engine map. Likewise, transmissions with a wider ratio spread can maintain engine operation nearer the highest efficiency areas of the engine map for a wider range of vehicle speeds, in particular lowering the engine speed at highway cruise for reduced GHG emissions.

In addition, the highest engine efficiencies for a given power output tend to be at lower speeds, so transmission control strategies that allow very low engine speeds (i.e., "downspeeding") also reduce GHG emissions. Shifting strategies are discussed in the "Transmission Shift Strategies" section below.

As a practical matter, transmissions with an increased number of gears tend also to have a wider ratio. For example, the ZF 8HP eight-speed RWD transmission has a spread of 7.07,[53] the Aisin eight-speed FWD transmission has a spread of 7.58,[54] the Mercedes 9G-TRONIC nine-speed transmission has a ratio spread of 9.15,[55] and the ZF 9HP48 nine-speed FWD transmission has a spread of 9.8.[56]

The effects of additional gears and a wider ratio can be seen in Figure 2.25, which compares engine operation of the same engine when coupled with a six-speed transmission and with an eight-speed transmission. Compared to the six-speed transmission, the eight-speed transmission allows the engine to operate over a narrower speed range and at lower speeds, both of which tend to reduce GHG emissions.



(a) Six-speed **(b) Eight-speed**

Figure 2.24 Engine Operating Conditions for Six-Speed (Left) and Eight-Speed (Right) Automatic Transmissions on the FTP-75 Drive Cycle[57]

The dominant trends in transmissions have been toward a larger number of gears and a wider ratio spread. However, it is recognized, including by the 2015 NAS Report, that above certain values, additional gearing and ratio spread provide minimal additional fuel economy benefits.[58] [59] [60] Thus, increasing the number of gears (except when going to effectively infinite the case of CVT transmissions) and ratio spread beyond that exhibited by the current market leaders is unlikely to result in significant fuel consumption benefits, although other vehicle attributes such as acceleration performance and shift smoothness may benefit.

In fact, it is well-understood that typical implementations of high-gear transmissions provide both fuel consumption and acceleration performance benefits. Performance benefits come from two factors: first, the gear ratio spread of transmissions with higher number of gears will typically "straddle" the ratio spread of the lower number of gear transmission they replace (i.e., first gear is a numerically higher ratio and the final gear is a numerically lower ratio). This provides more launch torque and quicker acceleration from stop. Second, the gear ratios of sequential gears tend to be closer together in transmissions with a higher number of gears. This not only narrows the on-cycle operation range of the engine for improved fuel economy (as in Figure 2.25), but also maintains engine performance nearer the maximum power point in high power demand situations for better acceleration performance at higher vehicle speeds.

To determine the relative cost-effectiveness of different technologies, it is important to account for *all* technology benefits where possible. As the NAS point out, "objective comparisons of the cost-effectiveness of different technologies for reducing FC can be made only when vehicle performance remains equivalent."[61] This is particularly relevant for advanced transmissions, which do affect performance when coupled with the same engine as transmissions with a lower number of gears. In evaluating information on measured or modeled fuel consumption effects of advanced transmissions, it is important to consider both reported fuel consumption benefits and any simultaneous acceleration performance benefits, so that transmission effectiveness can be objectively and fairly estimated.

Transmission design parameters that substantially affect engine operation - gearing ratios, ratio spread, and shift control strategy - are all used to optimize the engine operation point, and thus the effectiveness of these transmission parameters depend in large part on the engine it is coupled with. Advanced engines incorporate new technologies, such as variable valve timing and lift, direct injection, and turbocharging and downsizing, which improve overall fuel consumption and broaden the area of high-efficiency operation. With these more advanced engines, the benefits of increasing the number of transmission gears (or using a continually variable transmission) diminish as the efficiency remains relatively constant over a wider area of engine operation. For example, the NAS estimated that the benefit of an eight-speed transmission over a six-speed transmission is reduced by approximately 15 percent when added to a modestly turbocharged, downsized engine instead of a naturally aspirated engine.[62] Thus, the effectiveness of transmission speeds, ratio, and shifting strategy should not be considered as an independent technology, but rather as part of a complete powertrain.

Additionally, because the engine and transmission are paired in the powertrain, the most effective design for the engine-transmission pair is where the entire powertrain is running at the highest combined efficiency. This most effective point may not be at the highest engine efficiency, because a slightly different operation point may have higher transmission efficiency, leading to the best combined efficiency of the entire powertrain.

2.2.3.5 Automatic Transmissions (ATs)

Conventional planetary automatic transmissions remain the most numerous type of transmission in the light duty fleet. These transmissions will typically contain at least three or four planetary gear sets, which are connected to provide the various gear ratios. Gear ratios are selected by activating solenoids which engage or release multiple clutches and brakes. A cutaway of a modern RWD transmission (in this case the ZF 8HP70) is shown in Figure 2.25.

Figure 2.25 ZF 8HP70 Automatic Transmission[63]

Automatic transmissions are packaged with torque converters which provide a fluid coupling between the engine and the driveline, and provide a significant increase in launch torque. When transmitting torque through this fluid coupling, energy is lost due to the churning fluid. These losses can be eliminated by engaging ("locking up") the torque convertor clutch to directly connect the engine and transmission. A discussion of torque converter lockup is continued in the "Torque Converter Losses and Lockup Strategy" section below.

In general, ATs with a greater number of forward gears (and the complementary larger ratio spread) offer more potential for CO_2 emission reduction, but at the expense of higher control complexity. Transmissions with a higher number of gears offer a wider speed ratio and more opportunity to operate the engine near its most efficient point (as shown in the previous section).

In the past few years, manufacturers have taken advantage of this fact. Four- and five-speed automatic transmissions, which dominated the market in 2005, have substantially declined in number, being replaced by six-speed and higher transmissions (see Figure 2.22 above). In fact, the average number of AT gears in the fleet has rapidly increased, and in 2014 was above six for both cars and trucks (see Figure 2.26 below).

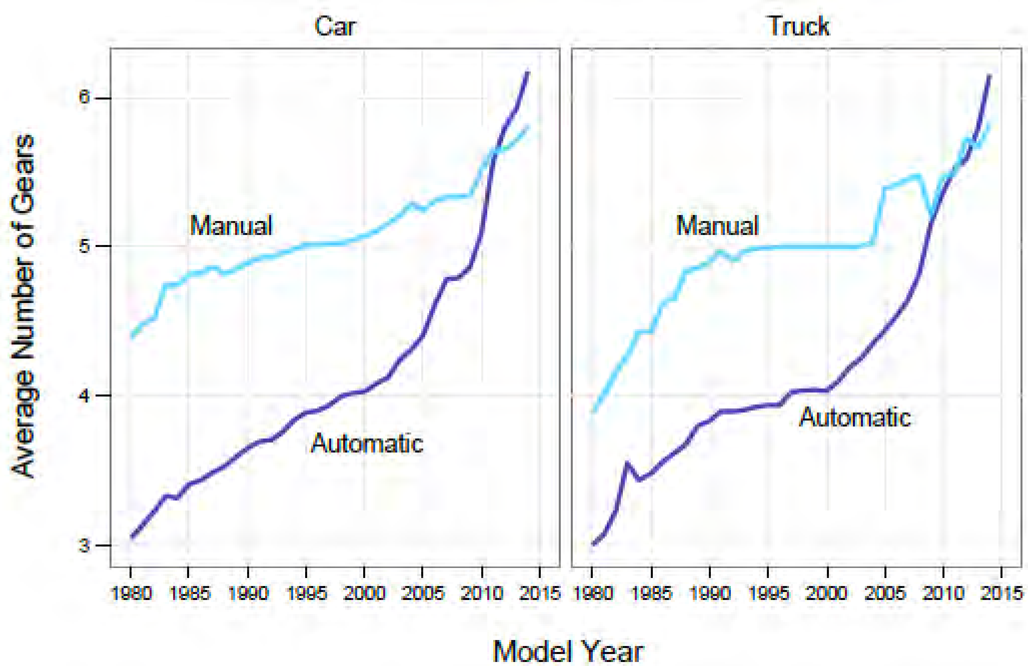


Figure 2.26 Average Number of Transmission Gears for New Vehicles (excluding CVTs)[64]

As six-speed ATs have supplanted the four-and five-speeds, seven- and eight-speed transmissions have also appeared on the market. As we mentioned in the Draft TAR, in the FRM, eight speed ATs were not expected to be available in any significant number until approximately 2020. However, even as of 2014 seven- and eight-speed transmissions occupy a significant and increasing portion of the market.

Seven-speed transmissions currently available include the RWD 7G-Tronic from Mercedes and the JATCO JR710E available in Nissan products. RWD eight-speed transmissions available include offerings from General Motors and Hyundai, as well as transmission suppliers Aisin and ZF. The ZF 8HP, introduced in 2009, has been incorporated into offerings from a range of manufacturers, including Fiat/Chrysler, Jaguar/Land Rover, and Volkswagen. ZF has begun production of a second generation of 8HP transmissions (the 8HP50), which features a higher ratio spread, lower drag torque, and improved torsional vibration absorption compared to the first generation.[65] Aisin also offers a FWD eight-speed used by multiple manufacturers. This includes use in the compact 2016 Mini Cooper Clubman,[66] a vehicle smaller than those assumed eligible for eight-speed transmissions in the FRM.

As mentioned in the Draft TAR, in the FRM, EPA limited its consideration of the effect of additional gears to eight-speed transmissions. However, some ATs with more than eight gears are already in production, and more examples are in development. At this time, nine-speed transmissions are being manufactured by ZF[67] (which produces a FWD nine-speed incorporated into Fiat/Chrysler, Honda, and Jaguar/Land Rover vehicles[68]) and Mercedes[69] (which produces a RWD nine-speed). Ford has released a ten speed transmission in the F150 Raptor, and GM released a variation of the same ten speed in the 2017 Camaro ZL1. In addition, Ford and General Motors have announced plans to jointly design and build a nine-speed FWD transmission, and Honda is developing a ten-speed FWD transmission.[70]

Manufacturers have claimed substantial fuel consumption benefits associated with newer transmissions. ZF claims its first generation 8HP can reduce fuel consumption by 6 percent on the NEDC compared to a circa 2005 ZF 6HP, using the same engine, along with improving vehicle acceleration performance.[71] ZF also outlined a series of potential improvements to the first generation 8HP that could provide an additional 5 to 6 percent fuel consumption reduction on the U.S. combined cycle.[72] The second generation ZF eight-speed[73] is expected to achieve up to 3 percent efficiency gain on the NEDC due to the improvements noted above; ZF also outlined additional potential savings associated with a third generation eight-speed transmission.[74] Likewise, Mercedes clamed a 6.5 percent fuel consumption improvement on the NEDC with its nine-speed transmission compared to the previous seven-speed.[75] It should also be noted that the percent fuel consumption reported on the NEDC drive cycle will be different from the U.S. combined cycles.

In FWD vehicles, ZF claims its nine-speed FWD transmission reduces fuel consumption by 10 percent - 16 percent compared to an early- 2000s six-speed transmission.[76] Aisin claims its new FWD eight-speed transmission decreases fuel consumption 16.5 percent compared to an early generation six-speed, and nearly 10 percent compared to the previous generation six-speed.[77] In addition, the new eight-speed improves acceleration performance. BMW, using the Aisin FWD transmission, reports a 14 percent fuel consumption reduction on the NEDC over the previous six-speed transmission.[78]

These efficiency improvements are due to a range of design changes in the transmissions. In addition to improving the engine operation efficiency through changing the number of gears, overall ratio, and shift points, these transmissions also reduce parasitic losses, change torque converter behavior, and/or shift to neutral during idle. Mercedes claims a total of 6.5 percent fuel economy improvement on the NEDC by using its nine-speed 9G-TRONIC in place of the earlier generation seven-speed.[79] Of this, 2 percent is due to the change in the number of gears, ratio spread, and shift strategy, with the remainder due to transmission efficiency improvements.

With the positive consumer acceptance, higher effectiveness, and increasing production of transmissions with up to ten forward gears, it may be possible that transmissions with even more gears will be designed and built before 2025. Researchers from General Motors have authored a study showing that there is some benefit to be gained from transmissions containing up to 10 speeds.[80] However this appears to be near the limit for improved fuel consumption, and studies have shown that there is no added potential for reduction in CO_2 emissions beyond nine or ten gears.[81] [82] In fact, ZF CEO Stefan Sommer has stated that ZF would not design transmissions with more than nine gears: "We came to a limit where we couldn't gain any higher ratios. So the increase in fuel efficiency is very limited and almost eaten up by adding some weight and friction and even size of the transmission."[83] Although manufacturers may continue to add gears in response to consumer preference for other performance attributes, at this time we are not projecting that further increases will provide CO_2 emissions benefits beyond that of optimized eight, nine or ten-speeds.

2.2.3.6 Manual Transmissions (MTs)

In a manual transmission, gear pairs along an output shaft and parallel lay shaft are always engaged. Gears are selected via a shift lever, operated by the driver. The lever operates synchronizers, which speed match the output shaft and the selected gear before engaging the gear with the shaft. During shifting operations (and during idle) a clutch between the engine and transmission is disengaged to decouple engine output from the transmission.

Manual transmissions are in general lighter, cheaper to manufacture, and have lower parasitic losses than automatic transmissions. The 2015 NAS report found the overall energy loss in a manual transmission to be only about 4 percent, as compared to a 13 percent loss in automatic transmissions.[84]

As with ATs, the average number of gears in MTs has increased (Figure 2.26), albeit at a reduced rate compared to ATs. As in ATs, the higher number of gears and associated increase in ratio spread increases potential fuel savings.

However, manual transmissions have only a small market share, estimated at only 2.6 percent in MY2015 based on the data in the MY2015 GHG baseline. Automatic transmissions (ATs, CVTs, and DCTs) are more popular at least in part because customers prefer not to manually select gears.

2.2.3.7 Dual Clutch Transmissions (DCTs)

Dual clutch transmissions are similar in their basic construction to manual transmissions, but use two coaxial input shafts with two clutches to shift between the two shafts. By simultaneously opening one clutch and closing the other, the DCT “hands off” power from one shaft to the other, and thus to sequential gears. Unlike the MT, the DCT selects the appropriate gear automatically (as in an AT). DCTs offer an efficiency advantage over a typical automatic because their parasitic losses are significantly lower. In addition, DCTs in general do not require a torque converter, as gradually engaging the clutch (much like with a manual transmission) provides the application of launch torque.

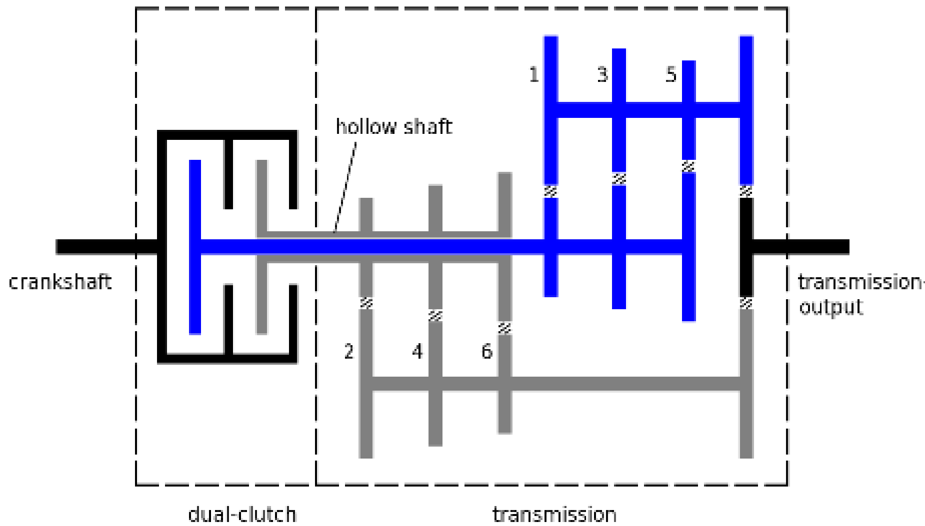


Figure 2.27 Generic Dual Clutch Transmission[85]

Multiple DCTs have been introduced into the marketplace, primarily in six- and seven-speed versions. Volkswagen has used multiple generations of DCTs in their products. Ford has used six-speed DCTs jointly developed with Getrag. Fiat has another version of a six-speed DCT, while both Honda and Hyundai have developed seven-speed versions. Honda introduced an eight-speed DCT with a torque converter on the 2015 Acura TLX.[86]

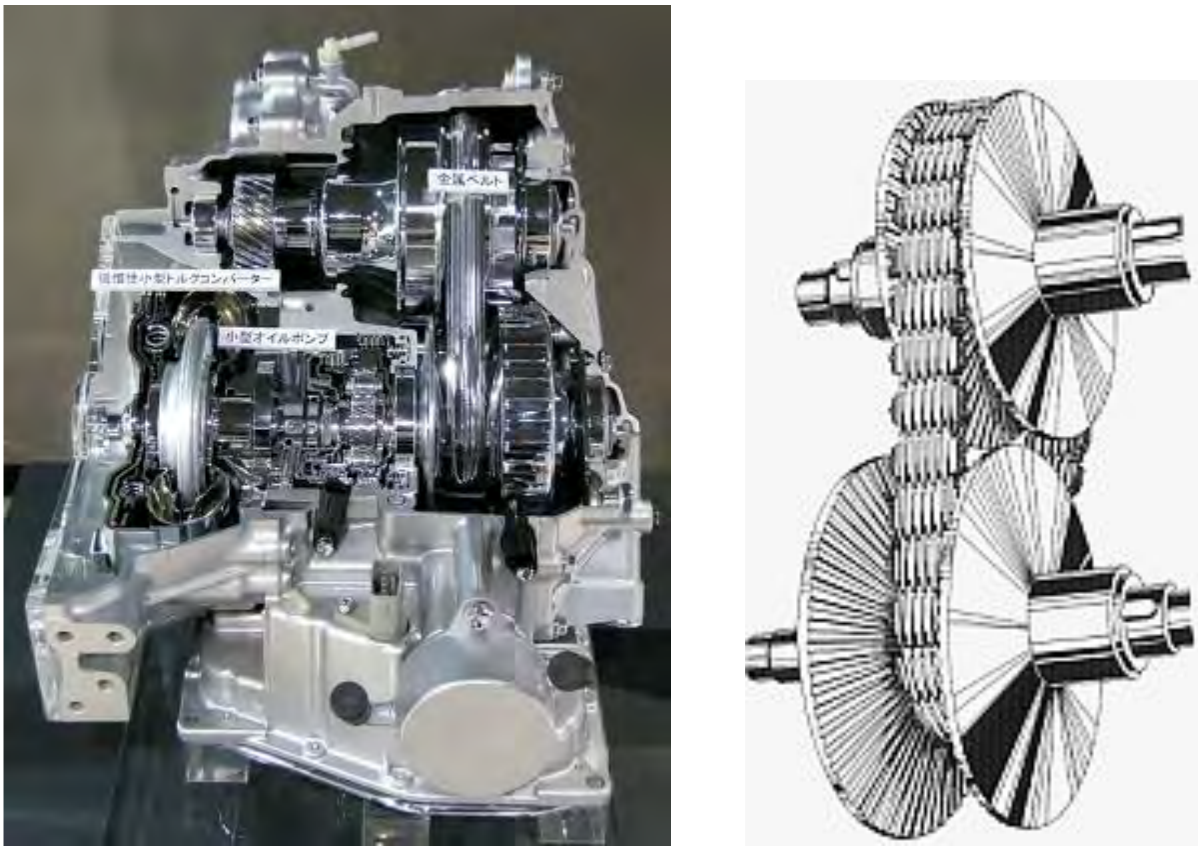
As mentioned in the Draft TAR, DCTs have encountered issues with customer acceptance, and, as the NAS stated in its 2015 report, "are not likely to reach the high penetration rates predicted by EPA primarily due to customer acceptance issues."[87] As noted by the NAS in their 2015 report, “This difference in drivability and consumer acceptance [between wet and dry clutch DCTs] can be seen in the comparison of two of Volkswagen's MY2015 vehicles, the VW Golf and the VW Polo. The Golf, with a wet-clutch DCT, has received many positive reviews and awards, while the Polo, with a dry-clutch DCT, has received poor reviews for transmission-related drivability."[88]

Getrag announced the 7DCT300 which has a wet clutch with lubrication on demand (we refer to these as damp clutch DCTs), equaling the efficiency of a dry DCT. The "damp" clutch is also smaller and has a higher tolerance for engine irregularities.[89] Wet/damp clutch DCTs tend to have better consumer acceptance than dry clutch DCTs. The 7DCT300 is available in Europe on the 2015 Renault Espace. Honda recently patented an 11-speed triple clutch transmission.

As in ATs, it is expected that additional gears above the current maximum will not significantly decrease fuel consumption and resulting GHG emissions. A 2012 study by DCT manufacturer Getrag indicated that additional gears above seven and additional ratio spread above 8.5 provided minimal additional fuel economy benefits.[90]

2.2.3.8 Continuously Variable Transmissions (CVTs)

Conventional continuously variable transmissions consist of two cone-shaped pulleys, connected with a belt or chain. Moving the pulley halves allows the belt to ride inward or outward radially on each pulley, effectively changing the speed ratio between the pulleys. This ratio change is smooth and continuous, unlike the step changes of other transmission varieties. CVTs were not chosen in the fleet modeling for the 2017-2025MY FRM analysis because of the predicted a low effectiveness associated with CVTs (due to the high internal losses and narrow ratio spans of CVTs in the fleet at that time). However, improvements in CVTs in the current fleet have increased their effectiveness, leading to rapid adoption rates in the fleet. In their 2015 report, the NAS recommended CVTs be added to the list of considered technologies, and EPA did indeed add re-evaluate the costs and effectiveness for this technology for its Draft TAR analysis and is continuing to consider CVTs in this Proposed Determination analysis.



(a) (b)

Figure 2.28 (a) Toyota CVT[91] (b) Generic CVT sketch[92]

One advantage of CVTs is that they continue to transmit torque during ratio changes. During a ratio change or shift the energy from the engine is wasted on ATs and some DCTs. ATs and some DCT have a hesitation during shifts caused by the torque disruption during gear changes. This shift feeling is well known to consumers and in some cases comforting to drivers (they miss it when driving a vehicle with a CVT). As mentioned in the AT section ATs efficiency peaks with 9 to 10 gears, while going to a CVT (with an effectively "infinite" number of gear steps) adds a new level of efficiency to the overall system. This is in part due to the fact that CVTs do not need to stop transmitting torque to change ratios.

Another advantage of a CVT is that, within its ratio range, it can maintain engine operation close to the maximum efficiency for the required power. However, CVTs were not considered in the FRM because at the time CVTs had a ratio range of near 4.0, limiting the range where the engine operation could be optimized. In addition, the CVTs were less than 80 percent efficient [93], and thus required more total output energy from the engine. These limitations overwhelmed the CVT's inherent advantage compared to conventional ATs.

However, in the recent past, manufacturers and suppliers have intensified development of CVTs, reducing the parasitic losses and increasing the ratio spread. The current generation of CVT are now nearly 85 percent efficient, with ongoing work by suppliers to push that number to 90 percent.[94] Ratio spreads for new CVTs from Honda, Toyota, and JATCO now range between 6.0 and 7.0. [95,96,97] JATCO has introduced a very small CVT what has a two speed output with take a CVT with a small ratio spread and doubles it for an overall ratio spread of 7.3[98] in the base version and 8.7 in the "wide range" version.[99] As in ATs and DCTs, it is expected that additional increase in ratio range above the current maximum will not significantly decrease fuel consumption and resulting GHG emissions. [100]

Reducing losses in CVTs has been a particular focus of manufacturers. The JATCO CVT8 featured a 40 percent reduction in mechanical losses compared to their earlier generation CVT.[101] The losses were reduced by decreasing the size of the oil pump, implementing a new, higher efficiency belt, and reducing the fluid churning losses. Honda's new compact car CVT increased efficiency 1.0 percent to 1.5 percent at higher vehicle speeds compared to their previous generation CVT.[102] The increased efficiency was primarily due to a reduction in oil pump losses and bearing friction. Honda's new midsize CVT increased efficiency up to 5 percent compared to the earlier generation CVT, primarily by reducing the required hydraulic pressure (by up to 38 percent).[103] Toyota's new K114 CVT reduced torque losses by 22 percent, compared to the earlier generation of CVTs, primarily by reducing the losses associated with the oil pump, and reducing the size of the bearings. [104]

The decreased transmission losses (5 - 10 percent) and increased ratio spread (from 4 to between 6 and 8.7) of CVTs has made them more effective in CO_2 reduction than estimated in the FRM, and thus CVTs are anticipated to be used in an increasing share of the fleet (see Figure 2.22). The supplier JATCO supplies CVTs to Nissan, Chrysler, GM, Mitsubishi, and Suzuki [105] In addition, other manufacturers' – Audi, Honda, Hyundai, Subaru, and Toyota – all make their own CVTs.

The JATCO CVT8 demonstrated a 10 percent improvement in fuel economy for both the highway and city cycles compared to earlier generation CVTs. [106] Honda's new compact car CVT increased fuel economy approximately 7 percent compared to the earlier generation CVT over both the U.S. test cycle and the Japanese JC08 test cycle. [107] Honda's new midsize CVT increased fuel economy 10 percent over the earlier generation 5AT on the U.S. cycle, and 5 percent compared to the earlier generation CVT on the Japanese JC08 test cycle. [108] Toyota's new K114 CVT increased fuel economy by 17 percent on the Japanese JC08 test cycle compared to the earlier generation CVT. [109]

Some initial introductions of CVTs suffered from consumer acceptance issues, where customers complained of the "rubber band" feel of the transmission, due to the indirect connection between the driver's throttle input and the vehicle's acceleration response. To combat this perception, vehicle manufacturers have added a shift feel calibration to the CVT control strategy, which mimics the feel of a conventional AT.[110] This calibration, although having a slight effect on fuel economy, has improved consumer acceptance.[111]

In this document, only conventional belt or chain CVTs are considered. At least two other technologies – toroidal CVTs and Dana's VariGlide® technology[112] – are under development and may be available in the 2020-2025 time frame. The Dana VariGlide is considered a CVP (Continuously Variable Planetary) with the major design difference being it using balls to transmit torque and vary the ratio. Dana has stated that it is currently in development with an OEM. Targeted production could be as early as 2020. These technologies hold promise for increased efficiency compared to current design belt or chain CVTs.

2.2.3.9 Transmission Parasitic Losses

Reducing parasitic loses in the transmission improves drivetrain efficiency and lowers the required energy output from the engine. In general, parasitic losses can come from (a) the oil supply, (b) electricity requirements, (c) drag torque, (d) gearing efficiency, and (e) creep (idle) torque.[113]

2.2.3.9.1 Losses in ATs

A study by ZF suggests that the largest sources of losses over the combined city/highway cycle in conventional automatic transmissions are the oil supply and the drag torque.[114] This is followed by the creep torque (on the city cycle), with the electrical requirements and gearing efficiency being relatively minor.

For conventional ATs, power required to supply oil to the transmission is one of the largest sources of parasitic loss. An oil pump is required for lubrication and for hydraulic pressure for clamping the clutches. A baseline transmission would typically use a gerotor-type pump driven off the torque converter. Replacing or resizing the oil pump can result in a substantial decrease in torque losses. For example, Aisin claims a 33 percent reduction in torque loss in its new generation transmission from optimizing the oil pump,[115] and Mercedes claims a 2.7 percent increase in fuel economy on the NEDC by changing the pumping system.[116] Pump-related losses can be reduced by substituting a more efficient vane pump for the gerotor. Losses can be further reduced with a variable-displacement vane pump, and by reducing the pressure of the system. Losses can be further decreased by using an on-demand electric pump: Mercedes claims an additional 0.8 percent increase in fuel economy on the NEDC by implementing a lubrication on demand system.[117] Another way to reduce losses from the pump is by reducing leakage in the system. Reducing leakage reduces parasitic losses by reducing the amount of fluid that needs to be pumped through the system to maintain the needed pressure.

A second large source of parasitic loss in ATs is the drag torque in the transmission from the clutches, brakes, bearings, and seals. These components have the potential to be redesigned for lower frictional losses. New clutch designs offer potential reductions in clutch drag, promising up to a 90 percent reduction in drag.[118] Replacing bearings can reduce the associated friction by 50 to 75 percent. New low-friction seals for can reduce friction by 50 percent to provide an overall reduction in bearing friction loss of approximately 10 percent.[119]

Optimizing shift elements improved fuel economy on the Mercedes 9G-TRONIC by 1 percent over the NEDC.[120]

Drag torque can be further reduced by decreasing the viscosity of the automatic transmission fluid used to lubricate the transmission. A study of transmission losses indicates that about a 2 percent fuel consumption reduction was obtained on the FTP 75 cycle by switching to the lowest viscosity oil.[121] However, reduction of transmission fluid viscosity may have an adverse effect on long-term reliability.

Transmission efficiency may also be improved through superfinishing the gear teeth to improve meshing efficiency.

2.2.3.9.2 *Losses in DCTs*

Advanced DCTs typically have lower losses than ATs, largely due to having an on-demand pump, splash lubrication, and fewer open clutches. The primary losses in DCTs are load-independent drag and splash losses. Unlike ATs, DCTs typically depend on splash lubrication for their internal components rather than forced lubrication. This eliminates the losses associated with oil supply pumps, but adds churning losses due to rotating components moving through the oil. Churning losses can be minimized by keeping oil levels low and warming up the lubrication oil.

A primary consideration in DCT losses is the use of wet or dry clutches.[122] Dry clutches do not require oil cooling flow, and therefore do not contribute to oil churning losses that are incurred with wet clutch systems; this has traditionally meant that dry clutch reduced GHG emissions by an additional 0.5 to 1 percent over wet clutch DCTs. However, dry clutches have a limited maximum torque capacity, and have suffered from customer acceptance issues. In response, so-called "damp" clutches have been introduced, where on-demand cooling flow has substantially reduced the parasitic losses associated with wet clutches.

DCTs also may benefit from the same improvements in bearing and seal drag and gear finishing that are outlined in the AT section above.

2.2.3.9.3 *Losses in CVTs*

CVTs tend to have higher losses than either ATs or DCTs, in large part due to the high oil pressures required to keep the belt and pulleys securely clamped. These losses increase significantly at high input torques, as even higher pressures are required to maintain the clamping force.[123]

A study by JATCO suggests that losses in the CVT are dominated by oil pump torque and losses in the belt-pulley system, with fluid churning losses as the next largest player.[124] By reducing leakage in the oil system and reducing line pressure when possible, JATCO's CVT8 was able to run with a reduced size oil pump and considerable reduction in oil pump torque loss. JATCO also redesigned the belt for lower loss, and reduced the oil level and viscosity to reduce churning losses. The overall result was a 40 percent reduction in mechanical losses compared to the earlier generation CVT.

Honda developed a new CVT using a comparable strategy.[125] They decreased the required pulley thrust by refining the control strategy and by using a fluid with increased coefficient of friction, which combined for a transmission efficiency increase of 2.8 percent. They also altered the belt trajectory around the pulley for an added 0.4 percent efficiency increase.

Another opportunity for reduced losses in CVTs is Dana's VariGlide System. Dana's VariGlide system can provide more favorable system losses than traditional belt or chain technologies. The VariGlide system eliminates the requirement for a high pressure pump, using instead a fully passive mechanical clamping mechanism. The unique coaxial configuration, similar to a planetary gearset coupled with high power density, allows for simple integration into traditional transmission architectures and makes it uniquely suited for RWD applications.

2.2.3.9.4 Neutral Idle Decoupling

An additional technology that has been implemented in some transmissions, which was not considered in the FRM, is the application of a "neutral idle." In this strategy, a neutral clutch is opened when the vehicle is at a stop, which effectively reduces the creep torque required from the engine.[126,127] BMW demonstrated a reduction in fuel consumption of 2 - 3 percent on the NEDC for an optimized neutral idle decoupling system on an eight-speed transmission.[128] Similarly, ZF calculated that implementing a neutral idle decoupling system on its eight-speed transmission would reduce fuel consumption by 0.5 percent to 1.4 percent on the U.S. combined cycle, depending on the K-factor of the torque converter.[129] It should be noted, of course, that the neutral idle decoupling simply reduces idling losses, and implementing stop-start system would eliminate the effectiveness of this technology.

2.2.3.10 Transmission Shift Strategies

The transmission shift schedule can strongly influence the fuel consumption over a drive cycle. A more aggressive shift schedule will downshift the transmission earlier and upshift later (i.e., at lower engine speeds). This moves engine operation, for a particular required power, to lower speeds and higher torques where engine efficiency tends to be higher. Along with this, reducing time between shifts (i.e., allowing more shifts), reducing the minimum gear where fuel cutoff is used, and altering torque converter slip (covered in the next section) will also decrease fuel consumption. Applying an aggressive shift strategy can reduce fuel consumption by about 5 percent in a generic six-speed transmission or 1-3 percent in a generic nine-speed transmission.[130] Similarly, BMW showed about a 2 percent reduction in CO_2 from downspeeding the engine, comparing their current generation six-speed transmission to an earlier generation.[131]

However, the application of the strategy is limited by NVH and drivability concerns, as lower engine speeds produce more significant driveline pulses and allowing more shifts may increase a shift busyness perception. Manufacturers reduce the NVH impact by using allowing partial lockup, adding a torque convertor dampener, and/or adding a pendulum dampener. These changes along with decreasing the ratio between gears has made higher gear numbers and increased shifting more acceptable. Reducing the ratio between gears allows shifting to be less perceptible due to the smaller change in engine speed.

2.2.3.11 Torque Converter Losses and Lockup Strategy

Torque converters are typically associated with conventional ATs and CVTs, although they have appeared on Honda's eight-speed DCT. Torque converters provide increased torque to the wheels at launch, and serve as a torsional vibration damper at low engine speeds. However, this comes at the cost of energy loss in the torque converter fluid, and modern torque converters typically have a lockup clutch that mechanically locks the impeller and turbine together, bypassing the fluid coupling.

Figure 2.29 ZF Torque Converter Cutaway[132]

Although in the past torque converters remained unlocked up to high vehicle speeds, recent trends are to lock up at much lower speeds. Improvements in torsional vibration dampers, and the ability to utilize micro-slip across the lockup clutch has enabled lower lockup speeds. Mazda, for example, claims torque converter lockup as low as 5 mph for its SKYACTIV-Drive AT.[133] Although not as aggressive, BMW claims a 1 percent reduction in CO_2 from an early torque converter lockup.[134]

2.2.4 Electrification: State of Technology

Electrification includes a large set of technologies that share the common element of using electrical power for certain vehicle functions that were traditionally powered mechanically by engine power. Electrification can thus range from electrification of specific accessories (for example, electric power steering) to electrification of the entire powertrain (as in the case of a battery electric vehicle). Powering accessories electrically can reduce their energy use by allowing them to operate on demand rather than being continuously driven by the crankshaft belt. Some electrical components may also operate more efficiently when powered electrically than when driven at the variable speed of a crankshaft belt. Electrified vehicles that use electrical energy from the grid also provide a means for low-GHG renewable energy to act as a transportation energy source where it is present in the utility mix. The addition of a larger capacity battery in a vehicle also provides for energy recovery or recuperation. Kinetic energy can be used to charge the battery and that recovered energy can be used to power accessories or to provide propulsion.

Electrified vehicles (or xEVs) are considered for this analysis to mean vehicles with a fully or partly electrified powertrain. This includes several electrified vehicle categories, including: battery electric vehicles (BEVs), which have an all-electric powertrain and use only batteries for propulsion energy; plug-in hybrid electric vehicles (PHEVs), which have a primarily electric powertrain and use a combination of batteries and an engine for propulsion energy; and hybrid electric vehicles (HEVs), which use electrical components and a battery to manage power flows and assist the engine for improved efficiency and/or performance. HEVs are further divided into strong hybrids (including P2 and power-split hybrids) that provide strong electrical assist and in many cases can support a limited amount of all-electric propulsion, and mild hybrids (such as belt integrated starter generator (BISG) hybrids, crankshaft integrated starter generator (CISG) hybrids, and 48V mild hybrids) that typically provide only engine on/off with minimum electrical assist. BEVs and PHEVs are herein referred to collectively as plug-in electric vehicles, or PEVs.

Fuel cell electric vehicles (FCEVs) are another form of electrified vehicle having a fully electric powertrain, and are distinguished by the use of a fuel cell system rather than grid power as the primary energy source. FCEVs have only recently entered commercial production and their market has not yet developed as much as that of PEVs. Technology developments relating to FCEVs were reviewed in detail in Draft TAR Chapter 5.2.4.5. Because EPA did not include FCEVs in its fleet compliance modeling analysis for the Draft TAR nor for the Proposed Determination, please refer to the Draft TAR for additional information on this technology.

As with the other technologies presented in this chapter, EPA has reviewed, and revised where necessary, the assumptions for effectiveness and cost of electrification technologies for this Proposed Determination. This effort extends the effort carried out for the Draft TAR, which included inquiries along several paths. As discussed in the Draft TAR, EPA gathered information from many sources, including public sources such as journals, press reports, and technical conferences, as well as manufacturer certification data and information gathered through stakeholder meetings with OEMs and suppliers. EPA has also benchmarked selected vehicles by means of dynamometer testing at the EPA National Vehicle and Fuel Emissions Laboratory (NVFEL), as well as utilized instrumented vehicle test data from the Argonne National Laboratory (ANL) Advanced Powertrain Research Facility (APRF). Among other purposes, EPA has used this data to inform development of the ALPHA model. EPA also utilized electric machine component performance data collected by Oak Ridge National Laboratory (ORNL) under U.S. DOE funding, and similar component and vehicle test data provided by other laboratories such as Idaho National Laboratory (INL). EPA also worked closely with ANL to improve and update the battery costing model, known as BatPaC,[135] which was used to update the projected costs of electrified vehicle battery packs. All of these sources have contributed to our assessment of the progress of electrification technology, an assessment that has continued since the 2012 FRM and before.

2.2.4.1 <u>Overview of Chapter</u>

This Chapter 2.2.4 is intended to review the current state of electrification technology as represented by developments since the 2012 FRM to the present, including updates since the Draft TAR that could inform the Proposed Determination assessment. The information described in this section thus forms the basis for revised cost and effectiveness assumptions described in Chapter 2.3.4.3, which become inputs to the Proposed Determination analysis. Source data for many of the charts in this Chapter and Chapter 2.3.4.3 are available in the Docket.[136]

This Chapter 2.2.4 is organized in the following way:

Chapter 2.2.4.2 provides a high-level overview of the major developments in electrification technologies since the 2012 FRM. This section is intended only as an executive summary to help place the topic of electrification into context.

Chapter 2.2.4.3 provides a background in non-battery electrical components that are common to many of the electrification technologies, and briefly reviews the major directions of their development since the 2012 FRM. An understanding of these components is helpful to understanding developments in cost and effectiveness of each of the electrified vehicle categories. Developments in the cost or performance of specific classes of components are discussed in the context of the electrified vehicles in which they have been implemented.

Chapter 2.2.4.4 includes subsections detailing each of the major electrified vehicle categories (stop-start, mild/48V and strong HEVs, PHEVs and BEVs). These subsections serve to briefly review the significance of each electrified vehicle category as a means of reducing GHG emissions, and review industry developments relating to how the category has evolved and been taken up in the fleet since the 2012 FRM.

Chapter 2.2.4.5 focuses on developments in battery technology. Batteries are discussed separately and after discussion of the electrified vehicle categories for several reasons. First, the battery performance requirements for each of the categories is best understood after the categories have been fully defined and discussed. Second, a greater level of technical detail is required to adequately assess some battery developments that have a strong influence on effectiveness or cost of xEV technologies. Finally, and perhaps most importantly, battery cost estimation is a particularly influential input to the cost assumptions for xEVs, and the battery cost estimates for different xEV categories rely on many detailed parameters that are best understood and contrasted in the context of a battery discussion after trends in xEVs have been reviewed. The bulk of battery-related developments are therefore covered in the battery chapter rather than the electrified vehicle category subsections.

Chapter 2.2.4.6 acknowledges developments in FCEVs, and refers the reader back to the more complete analysis of this technology that was published as Chapter 5.2.4.5 of the Draft TAR. Because EPA did not include FCEVs in its fleet compliance modeling analysis for the Draft TAR nor for the Proposed Determination, the assessment of FCEV technology is not repeated in this TSD.

Although these chapters may in some places refer to comments received on the Draft TAR, comments relating to electrification are primarily discussed in the context of specific modeling assumptions and inputs in Chapter 2.3.4.3.

2.2.4.2 Overview of Electrification Technologies

Throughout the 2012 rule analysis, and the Draft TAR analysis, electrified vehicles have been identified as offering a strong potential for reducing greenhouse-gas emissions. In all of these analyses, the cost-minimizing compliance pathway showed electrified vehicles playing an important supporting role in a fleet composed primarily of non-electrified powertrain configurations. For example, the pathway presented by EPA in the Draft TAR showed OEM compliance with MY2025 GHG standards with fleet penetrations of less than 3 percent BEVs, 3 percent strong hybrids, and 18 percent mild hybrids.[137]

In the years since the final rulemaking, the number of HEV, PHEV, and BEV models available to consumers has continued to grow. HEVs are now part of the product line of almost every major OEM. In 2014, U.S. HEV sales were in excess of 450,000 units. This declined to about 385,000 units in 2015.[138] Through September 2016, U.S. HEV sales are at approximately 260,000 units, which would represent a drop of about 13 percent compared to the same point in 2015.[139] Plug-in vehicles (BEVs and PHEVs) are also being offered in increasing numbers. In MY2015, 28 models of plug-in vehicles were available, an increase from 23 models in MY2014, and only a handful in 2012. In each of 2014 and 2015, U.S. plug-in vehicle sales were in excess of 115,000 units,[138] and through September 2016 are already at about 110,000 units.

Also in 2015 and 2016, a growing number of manufacturers announced ambitious plans to introduce multiple lines of plug-in vehicles by 2020-2025, including Volkswagen (planning more than 30 new all-electric vehicles with annual sales of 2-3 million units, or 20-25 percent of total sales, by 2025),[140,141] Mercedes-Benz (all models to be electrified in a similar time frame),[142] BMW (plug-in hybrid versions of all of its core models),[143] Volvo (battery electric power on all vehicles within the next decade),[144] and Ford (13 new BEV nameplates and 40 percent electrification by 2020).[145] In November 2016, it was reported[146,147] that even Toyota, which had previously concentrated primarily on fuel-cell and hybrid technology, is planning to add BEVs to its lineup by 2020.

In the Draft TAR, it was noted that some aspects of BEV implementation and penetration have developed differently than originally predicted in the 2012 FRM. At that time the agencies expected that BEVs with a range between 75 and 150 miles would be most likely to play a significant part in OEM compliance. By the time of the Draft TAR it was clear that the BEV market had developed two distinct segments, a consumer segment offering a driving range of around 100 miles at a relatively affordable price, and a premium segment offering a much higher range (well in excess of 200 miles) at a higher price. Tesla Motors has had notable success at producing and marketing BEVs in the premium segment, causing significant numbers of long-range BEVs to enter the fleet that may not have been predicted by OMEGA on a pure cost-effectiveness basis. Going forward, both BEV segments appear to be aggressively pursuing range increases in their second and third generation models. In 2016 GM announced the 2017 Chevy Bolt, which has been EPA certified with a 238-mile range. Nissan has also announced plans to offer a 200-mile range BEV in 2017 or 2018, using a newly developed battery pack. Tesla is also making progress toward a long-stated intention to enter the consumer segment with the Model 3, which is targeted for introduction in late 2017 and is expected to offer a range of at least 215-miles.

An increasing number of OEMs are beginning to add PHEVs to their product lines, utilizing both blended-operation architectures as well as extended-range architectures that offer varying amounts of all-electric range. The cost-minimizing pathway presented in the Draft TAR for compliance with the 2025MY GHG standards projected less than 2 percent fleet-level penetration of PHEVs.[148] The 2015 and 2016 MYs saw a discernible increase in PHEV20-style architectures from OEMs that tend to specialize in luxury or high-performance vehicles, which was consistent with projections in the 2012 FRM.[149] Second-generation PHEV models have begun to appear, typically offering an increased all-electric range or a more robust blended-mode operation that allows for increased all-electric capabilities in normal driving. Manufacturers have often cited customer demand for a more all-electric driving experience in making these changes.

Charging infrastructure is also growing. While PEVs are manufactured with onboard chargers that can often take advantage of existing 110V or 220V charging connections in the home or garage, opportunities for public charging away from the home are poised to become much more common. Since 2008, various ongoing public and private efforts to provide charging stations at workplaces, along freeway corridors, and in cities have grown the number of public stations in the U.S. to more than 16,000.[150] Since the Draft TAR was completed, two developments were announced that may increase this number substantially. The partial settlement between Volkswagen and U.S. authorities, approved in 2016, earmarks $1.2 billion in investment over 10 years toward ZEV infrastructure, education, and access.[151] Also, in November 2016 The White House announced a network of federal, state, and local initiatives to increase accessibility to PEV infrastructure,[150] including a Department of Transportation (DOT) plan to designate 48 national "alternative fuel corridors" along major highways to provide focus for build out of charging locations by related local and state efforts.[152] Public charging infrastructure was explored in depth in Draft TAR Chapter 9 (Infrastructure Assessment), and is reviewed for this Proposed Determination assessment in Section B.3.2 of the Proposed Determination Appendix.

Advancements in the cost and effectiveness of xEVs are closely related to advancements in battery, electric motor, and power electronics technologies. These technologies have advanced steadily since the 2012 FRM, with significant improvements in battery specific energy, battery cost, and non-battery component efficiency and cost contributing to improvements in production xEVs. The pace of industry activity in this area suggests that further advancements are likely to occur between now and the 2022 to 2025 time frame of the rule.

At the time of the 2012 FRM, data regarding the cost and efficiency of xEV components was limited by the small number of production vehicles from which it could be gathered. Today, the relatively large number of production models provides much greater opportunity to empirically validate projections made in the FRM.

Battery cost is a major consideration in the cost of xEVs. At the time of the 2012 FRM there was great uncertainty in the potential for battery manufacturing costs to be reduced. There was also uncertainty regarding battery lifetime. Today, evidence of the need for battery replacement is rare, with most PHEV and BEV batteries showing good durability within the limits established by OEM warranties. Although the battery cost projections published in the 2012 FRM were significantly lower than estimates of prevailing costs at the time, and those presented in the Draft TAR were even lower, evidence continues to suggest that these estimates were conservative, with at least one major manufacturer having announced battery costs from a major battery supplier that are very close to the Draft TAR projections. Recent reports have suggested that lithium-ion battery cost has historically followed a pace of improvement of about 6 to 8 percent per year.[153] Advancements in cost and energy capacity of battery technology continue to be pursued actively by OEMs and suppliers alike, suggesting that there is room for further improvement within the 2022-2025 time frame of the rule. Projected battery costs were accordingly updated for the Draft TAR and are now being further updated for the Proposed Determination based on public comment and updated information gathered since the Draft TAR.

The Draft TAR presented an analysis of current and past production BEVs and PHEVs that showed that the 2012 FRM analysis assigned a significantly larger battery capacity per unit driving range than manufacturers ultimately found necessary to provide. The Draft TAR found that this was likely related to the chosen assumptions for parameters such as powertrain efficiencies, usable battery capacity, and application of road load reducing technologies. The Draft TAR analysis also showed that the industry achieved comparable acceleration performance with significantly lower motor power ratings than the 2012 FRM analysis anticipated. In other words, it was shown that in many ways the industry had found ways to do more with less, compared to many of the original predictions of the 2012 FRM analysis. The Draft TAR analysis incorporated these developments in its revised projections of battery cost.

Because the vehicle architecture for electrified vehicles is fundamentally different from that of conventionally-powered vehicles, the consumer experience is likely to be different as well. In particular, the fueling requirements of BEVs and PHEVs call for changes in accustomed fueling habits, some of which may improve convenience (e.g. the ability to charge at home) while others may pose a challenge (e.g. a relatively long fueling time). A BEV with limited range might not provide an exact substitute for a conventional vehicle for many consumers today, while at the same time electrified vehicles can provide benefits of quiet operation, reduced maintenance, and the potential integration with future mobility systems that might include shared and autonomous vehicles.

The primary factors that influence the cost and effectiveness of electrification technologies are the cost and efficiency of their components. These include: energy storage components such as battery packs; propulsion components such as electric motors; and power electronics components, such as inverters and controllers, that process and route electric power between the energy storage and propulsion components. For the purpose of this analysis, these components are divided into battery components and non-battery components.

Battery components have a particularly strong influence on cost of xEVs. Because developments in battery technology may apply to more than one category of xEV, they are discussed collectively in Chapter 2.2.4.5. That chapter details developments in battery-related topics that directly affect the specification and costing of batteries for all xEVs, such as usable capacity, durability, thermal management, and pack topology, among others.

Non-battery components have a strong influence on both cost and effectiveness of xEVs. Because non-battery technologies are important to understanding the differences in architecture among xEVs, they are introduced prior to discussion of the individual electrified vehicle categories in Chapter 2.2.4.3.

2.2.4.3 Non-Battery Components of Electrified Vehicles

Non-battery components largely consist of propulsion components and power electronics. Propulsion components typically include one or more electric machines (an umbrella term that includes what are commonly known as motors, generators, and motor/generators). Depending on how they are employed in the design of a vehicle, electric machines commonly act as motors to provide propulsion, and/or act as generators to enable regenerative braking and conversion of mechanical energy to electrical energy for storage in the battery. Power electronics refers to the various components necessary to route current between the battery system and the propulsion components, including such devices as inverters and rectifiers, DC-to-DC converters, motor controllers, and on-board battery chargers.

The energy efficiency of non-battery components is a continuing focus of industry research and development. The impact of resulting improvements in efficiency and overall system optimization therefore have been considered in updating the estimates of xEV effectiveness used in the Draft TAR and Proposed Determination analyses.

Costs of non-battery components have been declining since the 2012 FRM and are widely expected to continue to decline. However, compared to engines and other conventional powertrain components, many of which have been reduced to commodity products for many years, the market in xEV non-battery components is still not as fully developed. As OEMs seek non-battery components for their electrified products, they are less likely to encounter stock items that fully meet their requirements and therefore have often chosen to either produce them in limited numbers in-house, or to source them from suppliers that build to specification. While this dynamic may be expected to limit the potential for economies of scale to develop and be reflected in component costs in the near term, the Draft TAR noted that standardization and commoditization will likely grow as the industry matures. For example, the decision of LG to leverage its position as battery supplier to several OEMs by expanding into non-battery components is one example of industry movement in this direction. In a joint announcement with LG Chem in October 2015,[154] GM described LG's role not only as supplier of battery cells for the Chevy Bolt BEV but also as supplier of many of its non-battery components. LG's established role as battery supplier to multiple OEMs suggests that it may be planning to supply non-battery components across the rest of the xEV industry as well. As another example, in 2016 Siemens and Valeo announced the formation of a joint venture for the production of high-voltage components across the full range of electrified vehicle types, citing among other advantages "substantial synergies in manufacturing and sourcing" and a focus on global markets.[155] Developments such as these can promote the potential for economies of scale to develop, and may be a significant driver of cost reductions if they continue in the future.

2.2.4.3.1 *Propulsion Components*

The components that provide propulsion for xEVs are known variously as electric motors, traction motors, motor/generators, e-motors, or electric machines. In this discussion, they will be referred to either as electric motors or generators (depending on the functional context), or collectively as electric machines.

The two main types of electric machines currently seen in production xEVs are permanent-magnet motors (also known as synchronous motors) and induction motors (also known as asynchronous motors). Although the permanent-magnet motors used in xEVs are sometimes called brushless direct-current (DC) motors, these as well as induction motors are powered by alternating current (AC), which must be converted from DC battery current by an inverter.

In the duty cycles typical of xEV applications, permanent-magnet motors have certain advantages in energy efficiency due in part to the presence of integral permanent magnets to generate part of the magnetic field necessary for operation. However, these magnets add to manufacturing cost, particularly when they contain rare earth elements. In contrast, induction motors use copper windings to generate all of the magnetic field and can be manufactured without rare earth elements. Although the windings are significantly less costly than magnets, generation of the field in the windings is subject to additional I^2R losses that are not present in permanent magnet motors. In some conditions, this causes induction motors to be slightly less energy efficient than permanent-magnet motors,[156,157] although the choice between the two types of motor ultimately depends on the specific application.

The majority of current xEV products use permanent-magnet motors. Induction motors are found in products of Tesla Motors, as well as the Fiat 500e and Mercedes-Benz B-Class Electric Drive. The BMW Mini-e and the Toyota RAV4 EV, both now discontinued, also used induction motors; in the case of the RAV4, the motor was supplied by Tesla.

Another type of motor, the switched reluctance or axial flux motor, has recently been suggested for use in xEVs.[158,159] Although current examples of this technology are challenged by difficulties with controllability, vibration, and noise, in the future these motors may potentially offer a lower cost solution than either permanent-magnet or induction motors.

The Draft TAR noted that some manufacturers have demonstrated successful cost reductions in propulsion components since the 2012 FRM. For example, the use of rare-earth metals in permanent-magnet motors has been a target of cost reduction due to the high cost of these metals and potential uncertainty in their supply. The 2016 second-generation Chevy Volt reduced the use of rare-earths in its drive unit by more than 80 percent by using lower-cost ferrite magnets in place of rare-earths in one of its motors[160] and significantly reducing the rare-earth content of the other.[161] Another approach is seen in the BMW i3, which uses a hybridized motor design that combines aspects of the permanent-magnet motor and the reluctance motor, allowing rare earth content to be reduced by about half compared to a permanent-magnet motor of similar torque capability.[157]

Component integration has also contributed to lower costs. GM has cited integration of power electronics with the transmission and drive unit of the 2016 Volt as a significant enabler of cost reductions in that vehicle by eliminating long stretches of heavy cable and improving packaging efficiency.[162,163] Major changes to the configuration of the electric propulsion system reduced the total torque and power requirements, allowing the use of smaller bearings and rotors, and an increase in maximum motor speed to 11000 rpm from the 9500 rpm of the previous system. This led to a 20 percent reduction in motor volume and a 40 percent reduction in mass compared to the previous generation, as well as improved efficiencies. Similar improvements have propagated to the Cadillac CT6[164] and the Chevy Malibu Hybrid[165] through the sharing of related components. The 2016 Toyota Prius also utilizes improvements to the transaxle and motor that result in significant weight reduction and efficiency. A more compact motor design and an improved reduction gear allows for an improved power-to-weight ratio and provides for a 20 percent reduction in frictional losses.[166]

Industry activity is also focused toward improving the efficiency of propulsion motors. Although electric motors are already highly efficient (well in excess of 90 percent in many normal usage conditions), even small improvements in efficiency can pay significant dividends by reducing the battery capacity necessary for a given driving range. For example, GM has said that the increased range of the second generation Chevy Volt was achieved in part by improvements in motor efficiency.[162] Even the first generation of the Chevy Spark EV was described as having the highest drive unit efficiency in the industry, with an average battery-to-wheels efficiency of 85 percent in the city cycle and 92 percent in the highway cycle.[167] These efficiencies are higher than EPA had assumed in the 2012 FRM xEV battery sizing analysis.

2.2.4.3.2 Power Electronics

Power electronics refers to the various components that control or route power between the battery system and the propulsion components, and includes components such as: motor controllers, that issue complex commands to precisely control torque and speed of the propulsion components; inverters and rectifiers, that manage DC and AC power flows between the battery and the propulsion components; onboard battery chargers, for charging the BEV or PHEV battery from AC line power; and DC-to-DC converters that are sometimes needed to allow DC components of different voltages to work together.

Inverters are power conditioning devices that manage electrical power flows between the battery and propulsion motors. While all batteries are direct current (DC) devices, modern traction motors operate on alternating current (AC) and therefore require an inverter capable of converting DC to AC of widely variable frequencies at variable power levels. As implemented in an electrified vehicle, the component commonly known as an inverter may also act as a rectifier, that is, convert AC to DC to send energy to the battery.

Modern inverters are semiconductor based, utilizing metal-oxide-semiconductor field-effect transistors (MOSFET) or insulated-gate bipolar transistors (IGBT). These designs are highly efficient, often operating well above 90 percent efficiency. Inverter designs vary in output waveform (square wave, sine wave, modified sine wave, or pulse-width modulated), which accounts in part for differences in their efficiency and the potential for heat generation. Inverter manufacturing cost is strongly associated with wafer size in manufacturing of substrate materials such as silicon carbide. While most wafer sizes are currently around 4 inches in diameter, larger wafers of 6 to 12 inches would reduce scrap rates and reduce cost substantially.[168]

Despite these low losses, the high power levels of electrified vehicles generate significant heat and require inverters to have aggressive liquid cooling, often residing on the coolant loop in a position prior to the propulsion motor to ensure sufficient cooling. Cooling elements such as fans, heat exchange surfaces and fins or heat sinks can add to volumetric requirements and are a common target of size and cost reduction. The similarity of materials and cooling needs offer an opportunity to further reduce cost by integrating the inverter with other power electronics components such as DC converters.[169]

The 2016 Chevy Volt provides one example of how improvements to the inverter and its packaging can lead to significant improvements in packaging and related costs. Major changes to the electric propulsion system served to reduce the current requirements of the inverter, reducing its volume by about 20 percent (from 13.1L to 10.4L) and its mass from 14.6 kg to 8.3 kg. This allowed the inverter module to be integrated into a small space at the top of the transmission. This integration into the transmission saved on assembly costs, served to protect the components and their sensitive interfaces in a sealed environment, and eliminated the need for heavy 3-phase cables. It also saved valuable under-hood space for other components commonly associated with electrification. The reduction in inverter current was also said to reduce inverter switching loss by about half in conjunction with accompanying improvements to cooling. GM attributed a 6 percent improvement in electric drive system efficiency over the FTP cycle, a 30 percent increase in vehicle range and an 11 percent improvement in label fuel economy to these inverter improvements.[162,163] Similar improvements have carried over to other models that share related components, such as the Cadillac CT6 and the Chevy Malibu Hybrid.[164,165] Toyota also has introduced changes that improve inverter efficiency.[166] The 2016 Toyota Prius includes a new power control unit to which it attributes a 20 percent reduction in power losses. The power control unit also benefits from integration, residing in a position above the transaxle. Advances in the use of a silicon carbide substrate in the power control unit are also expected to significantly reduce power switching losses and allow a 40 percent reduction in the size of the coil and capacitor of the power control unit in production Toyota vehicles by around 2020.[170]

Many systems require DC-to-DC converters to allow DC components of different voltages to work together. They do not convert between AC and DC, but instead step up or down the DC voltage between two or more components or subsystems, either unidirectionally or bi-directionally. One common application of a DC-to-DC converter is to allow low-voltage accessories to be powered by energy from the high-voltage battery by reducing the voltage from 300+ V to 14 V. These are also known as buck converters, and commonly operate at about 1.5 kW[171] to 3 kW.[188] Although many current-production BEVs and PHEVs retain a low-voltage battery to power accessories, a buck converter is needed to keep the low-voltage battery charged in the absence of an engine-driven alternator, and can provide additional power to the accessories. Another purpose of a DC-to-DC converter is to allow certain powertrain components to operate at their optimum voltage rather than being tied to the voltage of the high voltage battery. For example, a fuel cell stack or super capacitor may operate more efficiently at a higher or lower voltage than the high-voltage battery, or along a variable range of voltages.[172] A variety of topologies are under development to suit these varied applications.[171,172]

Controllers are electronic devices that implement control algorithms that control power flows through the electrified powertrain. Motor controllers are responsible for issuing the complex commands that precisely control torque and speed of the propulsion motor. A primary task of this controller is to determine the exact frequency of alternating current necessary for the motor to deliver the demanded speed and torque, and to control the inverter to provide it. A supervisory controller is another form of controller that implements higher-level vehicle control algorithms, including issuing high-level torque and speed commands to the motor controller. Supervisory controllers are not unique to electrified powertrains but may be functionally integrated with other components that are. Compared to other power electronics components, controllers are not typically large consumers of energy, but can benefit from cost reductions applicable to other components.

Onboard chargers are charging devices permanently installed in a PHEV or BEV to allow charging from grid electrical power. Level 1 charging refers to charging powered by a standard household 110-120V AC power outlet. Level 2 charging refers to charging with 220-240V AC power. In practice, the charging power that is available in a given home installation may depend on the amperage capability of the household circuit. Typical household circuitry can usually support about 1 to 2 kW for Level 1 and about 5 to 7 kW for Level 2, although the SAE J1772 standard for Level 2 charging can support up to 19.2 kW with proper electrical service. Onboard chargers travel with the vehicle, and are distinct from stationary charging equipment (Electric Vehicle Supply Equipment, or EVSE) commonly installed at public or private charging stations.

The Draft TAR (in Chapter 9, Infrastructure Assessment) included an examination of PEV EVSE technology.

The widespread home availability of 110-120V AC power does not necessarily mean that Level 1 charging is preferable either for convenience or efficiency. Charging time at the Level 1 rate is much longer than at Level 2. At Level 1, some longer-range BEVs may take longer than overnight to bring from a low charge to full charge (although, for a given daily mileage, they may reach a low charge state less often, and are equally capable of having daily mileage replenished at Level 1 nightly). Level 1 residential charging is commonly relied upon by many of the current users of BEVs and PHEVs, and provides a lower cost option for ownership that may continue to be sufficient for households with lower daily driving needs.

Public charging infrastructure is also growing. As mentioned in the Draft TAR, since 2008, various ongoing public and private efforts to provide charging stations at workplaces, along freeway corridors, and in cities have grown the number of public stations in the U.S. from practically a handful to more than 16,000.[173] Since the Draft TAR was completed, two developments were announced that may increase the availability of public charging substantially. The partial settlement between Volkswagen and U.S. authorities, approved in 2016, earmarks $1.2 billion in investment over 10 years toward ZEV infrastructure, education, and access.[174] Also, in November 2016 The White House announced a network of federal, state, and local initiatives to increase accessibility to PEV infrastructure,[150] including a Department of Transportation (DOT) plan to designate 48 national "alternative fuel corridors" along major highways to provide focus for build out of charging locations by related local and state efforts.[175] Public charging infrastructure was explored in depth in Draft TAR Chapter 9 (Infrastructure Assessment), and is reviewed for this Proposed Determination assessment in Section B.3.2 of the Proposed Determination Appendix. Some additional discussion in the context of BEV technology is also found in Chapter 2.2.4.4.5 (Battery Electric Vehicles) of this TSD.

Charging efficiency can also vary significantly. In general, the efficiency with which a battery accepts DC charge current is higher at lower charge rates.[176] However, the degree to which the manufacturer has optimized the charging circuitry for a specific preferred charge rate can also have a strong influence, because the efficiency of AC to DC conversion is also an important factor. According to tests performed by Idaho National Laboratory on a 2015 Nissan Leaf, the efficiency of Level 1 charging ranged from only 61.8 percent to a maximum of 78.4 percent, while that of Level 2 charging ranged from 81.5 percent to 90.5 percent.[177] This suggests that the design of the charging circuitry can have a greater effect on charging efficiency than charge rate alone, and that manufacturers may optimize the charging system to accommodate the mode of charging it expects customers to most commonly utilize.

DC fast charging is increasing in availability and popularity, and can support charging at much higher rates than Level 2 (up to 150 kW in some cases, subject to the capability of the vehicle being charged). Charging at these higher rates may result in a lower net efficiency relative to Level 2, and may require more robust cooling of the battery and even the charging connection to dissipate the heat generated during a charge.

Although charging efficiency is primarily relevant to upstream emissions and is not a factor in onboard energy consumption, there is significant potential for efficiency improvement in these components that may be indicative of similar potential in other power electronics components. For example, between Gen1 and Gen2 of the Chevy Volt, the energy efficiency, size and weight of its onboard charger was improved significantly.[178,163] Level 1 charging efficiency improved from 86.8 percent in Gen1 to 94.5 percent in Gen2, an improvement of 8.9 percent. Efficiency at Level 2 increased similarly from 89.6 percent to 95.5 percent, an improvement of 6.6 percent. These improvements allowed the overall system efficiency (from the wall plug to the battery) of Level 2 charging to improve to 88.4 percent, and that of Level 1 to 86.7 percent (improvements of 8.6 percent and 9.3 percent, respectively). Power density of the unit improved from 326 W/kg to 605 W/kg (85 percent), while volumetric power density improved from 492 W/liter to 889 W/liter (81 percent), which led to significant packaging advantages. The fact that these improvements to charger efficiency were achieved despite their lack of a strong impact on highly visible attributes such as driving range or power suggests that similar improvements to other components that do affect range or power are even more likely to be pursued successfully.

Battery management systems (BMS)[179,330] are an important factor in maintaining and utilizing the available capacity of the traction battery. A primary role of a BMS is to maintain safety and reliability by preventing usage conditions that would damage or excessively degrade the battery. The BMS may therefore limit voltages and currents on the pack, module, or individual cell level, and monitor pack or cell temperature as well as other parameters.

Another important role of the BMS is to balance the charge levels of the individual battery cells so that each cell is maintained at a similar voltage and state of charge. This can play an important part in determining the usable portion of total battery capacity and in maintaining battery life. In a battery containing hundreds of cells, small variations in resistance will exist among individual cells, and differences in cell temperature will result not only from these differences but also from differences in cell location within the pack and proximity to cooling media. During a normal charge or discharge of the pack, these differences will affect cell efficiency and cause some cells to approach their voltage or charge limits sooner than others. Without balancing, the entire pack will effectively reach its charge or discharge limit when the weakest cell reaches its limit. In this case, the charge contained in the remaining cells goes unutilized. Effective cell balancing can increase utilization significantly.

BMS systems may employ passive or active balancing. Passive balancing acts to identify the cells that are approaching their limits and selectively modifies their charge or discharge rates, usually by dissipating their energy resistively, to allow the remaining cells to continue operating. Active balancing shuttles energy among cells rather than dissipating the energy. Active balancing is potentially more energy efficient than passive balancing but is typically costlier to implement. The cost and effectiveness of active balancing is an active area of industry research toward reducing the necessary battery capacity and power for a given application.

Somewhat counterintuitively, all current production BEVs have a conventional 12-volt lead-acid battery in addition to the high-voltage traction battery. There are many practical reasons why BEVs retain a low-voltage battery.[180] Although the engine starting function is no longer needed, a low-voltage power source is still needed for accessories and other functions. While a DC-DC converter is available to step down the voltage of the traction battery to a suitable voltage for the accessory bus (and in fact this is how the 12-volt battery is kept charged in the absence of an engine-powered alternator), it is not a complete substitute for a battery because neither the converter nor the high-voltage battery are kept in a powered state when the vehicle is parked. Starting the vehicle therefore requires, at minimum, a low-voltage power source to close the contactors and activate the high-voltage battery system. The vehicle may also continue to draw current from the low-voltage battery to perform BEV-specific functions even while the vehicle is off, perhaps for functions such as battery system maintenance and safety monitoring, in addition to the other current draws that are common to many conventional vehicles. The low-voltage battery may also act as a buffer between the DC-DC converter and the low-voltage bus, allowing the DC-DC converter to operate intermittently rather than continuously to keep the battery charged, and providing a stable voltage source to power sensitive microprocessor components in the control circuitry.

BEVs therefore may subject the 12-volt battery to a different duty cycle than in conventional vehicles. In recent years some evidence has accumulated that 12-volt lead-acid batteries in some BEVs are being replaced after a relatively short life; in many cases, replacement has been necessary on an almost annual basis.[181,182] Although Tesla is said to specify a deep-cycle lead-acid battery for the Model S, this battery is still reported to have a relatively short service life.[183]

In conventional vehicles, the size of the 12-volt battery tends to be correlated with the size of the engine, due to its function in engine starting. Because a BEV 12-volt battery does not perform this function, most BEVs can likely utilize a relatively small 12-volt battery regardless of the power of the vehicle. For example, the 12-volt battery of the Tesla Model S has a capacity of 33 Ampere-hours and weighs about 27 lb, smaller than the batteries found in conventional vehicles of a similar power capability.[184]

The low cost, familiarity, and widespread availability of lead-acid 12-volt battery technology is likely a factor in its selection as the basis for BEV low-voltage power. The potential tendency for a relatively short life in BEV applications would seem to suggest that over the longer term, other solutions such as a low-voltage lithium-ion battery may become competitive with lead-acid. Despite the higher initial cost of lithium-ion, it could be a more cost effective solution if it prevents multiple replacements of a lead-acid battery, particularly if the manufacturer anticipates that many of those replacements may occur during the warranty period. While lead-acid has traditionally performed better in cold weather, formulations of lithium-ion exist that are robust in cold weather, and may weigh about half of an equivalent capacity lead-acid battery,[185] potentially making the 12-volt battery almost an insignificant component of the total weight of the vehicle. The Hyundai Ioniq PHEV, scheduled for introduction in the U.S. market in 2017, has been described as eliminating the 12-volt battery, in favor of a 12-volt tap from the high-voltage battery pack.[186] Whether or not this innovation makes it into the production PHEV or the BEV version, it indicates that some PEV manufacturers are actively investigating alternatives to the conventional lead-acid low-voltage battery.

2.2.4.3.3 Industry Targets for Non-Battery Components

Establishing targets can be an effective way of focusing industry effort toward a common goal. For example, the battery cost and performance targets established by the United States Advanced Battery Consortium (USABC) are familiar to most in the battery industry and have become important reference points by which developments in battery technology are often measured. While industry targets such as these can vary in their purpose and achievability, they can provide valuable guidance on what some in the industry consider to be potential directions for future technology.

Targets for cost and performance of non-battery components have been established by U.S. DRIVE,[187] a government-industry partnership managed by the U.S. Council for Automotive

Research (USCAR), which also manages USABC. Members include the U.S. Department of Energy, industry members of USCAR, and several other organizations including major energy companies and public energy utilities. The U.S. DRIVE targets apply to electric motors, inverters, chargers, and other power electronics components for the 2015 and 2020 lab year[V] time frames.[188] These targets, some of which are shown in Table 2.1, include performance targets such as specific power, specific energy, and energy and power density (volumetric), as well as cost targets.

The U.S. DRIVE targets were established specifically with respect to HEVs, which were seen as presenting the greatest challenge in meeting the targets due to their being on the low end of the power range compared to PEVs. The targets therefore apply best to an HEV-sized 55 kW system. U.S. DRIVE expects the targets to be less difficult to meet for higher-power PEV systems, in part because their more powerful powertrains may incur less overhead cost (for connectors and the like) that are not necessarily directly proportional to power.[189] This suggests that the U.S. DRIVE targets would be relatively conservative when applied to PEVs.

Although the U.S. DRIVE figures are only targets, the industry has shown remarkable progress in approaching these goals. It is notable that U.S. DRIVE targets for specific power are quite close to what was already available in some production HEVs at the time they were set. Since some of the goals were being met in higher-priced products, bringing these levels of performance to the average PEV may largely be a matter of cost reduction rather than technological breakthrough.

Table 2.1 U.S. DRIVE Targets for Electric Content Cost and Specific Power

Component	U.S Drive Target (Lab Year)	
	2015	2020
Electric motor	1.3 kW/kg	1.6 kW/kg
	$7/kW	$4.7/kW
Power electronics	12 kW/kg	14.1 kW/kg
	$5/kW	$3.30/kW
Motor and electronics combined	1.2 kW/kg	1.4 kW/kg
	$12/kW	$8/kW
3 kW DC/DC converter	1.0 kW/kg	1.2 kW/kg
	$60/kW	$50/kW

The 2020 lab year target for specific power of combined motor and power electronics has some support in current literature. Assuming a five-year lag between lab demonstration and production, the 2020 lab year corresponds to 2025. A presentation by Bosch[190] at The Battery Show 2015 states that the electric motor and power electronics for a 100 kW, 20 kWh BEV system in the 2025 time frame is expected to comprise about 37 percent of electric content weight, with battery weight comprising the remaining 63 percent. Assuming the 20 kWh battery pack has a specific energy of about 140 Wh/kg (as indicated by ANL BatPaC for an NMC622

[V] It should be noted that a minimum of five years typically passes between successful demonstration of a technology in a lab and its introduction into the market.

pack at 115 kW net battery power), and a corresponding weight of 143 kg, the non-battery content would be estimated at about 53 kg. The 100 kW system would then represent a non-battery specific power of 100 kW/53 kg, or 1.88 kW/kg. While the U.S. DRIVE target of 1.4 kW/kg is not directly comparable because it is based on a 55 kW traction motor, the result for the 100 kW example is directionally correct in the sense that U.S. DRIVE considers the targets easier to achieve for more powerful systems.[189] Most BEV and PHEV motors modeled in this analysis are larger than 55 kW, suggesting that the U.S. DRIVE figure for a 55 kW system may represent a fairly conservative figure for these applications.

Although the U.S. DRIVE figures are targets and therefore not necessarily indicative of industry status, EPA has confidence that the targets for specific power represent attainable production goals during the time frame of the rule. This is based in part on the observation that the 2020 specific power target for electric motor and power electronics combined is very close to levels that were already being attained by some production vehicles at the time they were set.[191] Further, the motor of the recently announced Chevy Bolt BEV already appears to exceed the U.S. DRIVE target at 1.97 kW/kg (based on a mass of 76 kg and peak power of 150 kW).[192] This example is consistent with confidential business information conveyed to EPA through private stakeholder meetings with OEMs that suggests that cost and performance targets for some types of components are already being met or exceeded in production components today, or are expected to be met within the time frame of the rule.

2.2.4.4 Developments in Electrified Vehicles

In this Proposed Determination analysis, each of the electrified vehicle categories represents a distinct GHG-reducing electrification technology that manufacturers may choose to include as part of a compliance pathway. These technologies range from 12-volt stop-start systems without accompanying hybridization, to mild and strong hybrids (HEVs), to plug-in vehicles (PHEVs and BEVs) and fuel-cell electric vehicles (FCEVs). The propulsion and power electronics technologies discussed in the previous section are integral to understanding the architecture and capabilities of each of these electrification technologies. Developments in each of these electrification technologies are described in this section.

2.2.4.4.1 *Non-hybrid Stop-Start*

In this analysis, non-hybrid stop-start refers to a technology that reduces idling by temporarily stopping the engine when the vehicle stops, and restarting it when needed. This eliminates much of the fuel consumption associated with idling. In urban driving conditions that include a large amount of idling at intersections and in congested traffic, stop-start can provide significant GHG benefit.

Non-hybrid stop-start is also commonly known as idle-stop or micro hybrid. In the 2012 FRM, it was referred to as conventional stop-start. In this Proposed Determination analysis (as in the FRM and Draft TAR analyses), non-hybrid stop-start is limited to engine stopping and restarting in a 12V context, with no accompanying hybridization. For this reason, the term micro-hybrid will not be used to refer to non-hybrid stop-start systems. The non-hybrid stop-start classification should not be confused with mild and strong hybrids that include a stop-start function. Systems that include brake energy regeneration or other hybrid features would be classified as hybrids. However, as in the Ricardo analysis of the 2012 FRM, non-hybrid stop-start may include a strategy known as "alternator regen" that charges the 12V battery more aggressively by increasing the alternator field upon vehicle deceleration.

Non-hybrid stop-start is therefore the simplest form of electrification discussed in this section. It is typically implemented by: (a) upgrading to a higher-performance starter capable of higher power and increased cycle life, (b) upgrading to a higher-performance 12V battery to improve cycle life and reduce voltage drop on restart; (c) adding an appropriate control system to manage stopping and starting as transparently as possible; and in many cases, (d) modifying certain accessories to allow for adequate service while the engine is off.

As originally modeled in the 2012 FRM, the effectiveness estimates for stop-start were derived from the Ricardo modeling study, which estimated 2-cycle effectiveness to be in the range of 1.8 to 2.4 percent, depending on vehicle class. As originally represented in the 2012 FRM, stop-start was considered to be a new technology and was assigned a steep learning curve for the years 2012-2015 and a flat learning curve for the years 2016-2025. On the basis of projected costs and effectiveness, EPA projected that stop-start would achieve a fleet-level penetration of 15 percent[193] in the cost-minimizing pathway for compliance with the 2025MY standards.

As discussed in the Draft TAR, since the 2012 FRM, rapid growth in the application of 12V stop-start systems is evidence of the technology's potential to provide cost-effective emissions reductions. The 2015 EPA Trends Report projects that non-hybrid stop-start will be present on almost 7 percent of new non-hybrid car and truck production in MY2015, with total penetration of stop-start at nearly 9 percent when mild and strong hybrids are included.[194] Penetration has grown steadily each year, reaching 0.6 percent in 2012, 2.3 percent in 2013, and 5.1 percent in 2014, with 6.6 percent projected for 2015.[195] BMW and Mercedes-Benz are the most notable adopters, each including stop-start in about 70 percent of their projected 2015 production.[196] In comments on the Draft TAR, CALSTART described a survey of suppliers, performed by Ricardo. The comment indicated that suppliers in the survey consider stop-start to be among the top 5 technology strategies for meeting the 2025 standards. CALSTART also stated, "CALSTART has had a number of conversations with different suppliers who have indicated they are making major investments in 48V mild hybrid technology as a leading strategy to meet standards particularly in China and Europe."

As a GHG-reducing technology, the effectiveness of stop-start depends on the amount of idle time included in the assumed test cycle. The standard EPA test cycles contain short periods of idle, but less than some believe is present in real world driving. In order to provide a more accurate credit basis for the real-world benefit of stop-start, stop-start technology is eligible for off-cycle credits under the Off-Cycle Program. The Off-Cycle Program is discussed further in Chapter 2.2.10.

As discussed in the Draft TAR, in contrast to the 2012 FRM projections of 1.8 to 2.4 percent effectiveness under EPA test cycles, other sources have suggested an average of 3.5 percent.[197,198,199] As one example, the Draft TAR noted that the 2015 Ford Fusion 1.5L TGDI is available with and without a 12V stop-start option, providing an opportunity to assess the effectiveness of stop-start as implemented in this vehicle. The difference in estimated fuel economy between the two versions suggests an effectiveness of about 3.5 percent on a fuel economy basis. The automotive supplier Schaeffler Group has presented an engine stop-start technology[200] it describes as capable of providing a 2-cycle combined fuel economy improvement of about 6 percent over the city cycle and 2 percent over the highway cycle, or about 3.42 percent combined. The 2015 Mazda3 is available with and without the Mazda i-ELOOP regenerative braking and stop-start system. A comparison of certification test data for this vehicle with and without the system suggests that its two-cycle GHG effectiveness is about 3.35 percent.[201]

Some test cycles used in other parts of the world include a greater proportion of idle time and therefore assign a greater benefit to stop-start. This would naturally make stop-start more attractive to manufacturers in regions that certify under these cycles, and may be a factor in the greater penetration of stop-start that has been observed worldwide. Stop-start[197] has been popular in Europe due to high fuel prices and the stringent EU CO_2 emission target established in 2009. In 2014, about 60 to 70 percent of vehicles sold in the European market offered stop-start.

Because stop-start technology alters the customary operation of the engine, it has potential to alter the traditional feel of driving. Frequent restarts of the engine, although rapid and seamless in most implementations, can increase the sense of noise, vibration, and harshness (NVH). Drivers unaccustomed to stop-start may at first feel uncomfortable having the engine switch off in stop and go traffic, particularly if accessories such as heat or air conditioning are also affected. Some of the seamlessness and potential benefit of stop-start can be eroded by individual driving habits. For example, if a driver repeatedly pulls up toward the leading car as traffic compacts while waiting at an intersection, the engine may restart each time, reducing fuel savings and adding to NVH.

Manufacturers often cite consumer acceptance factors in the adoption of stop-start in the U.S market. Early introductions of the technology involved lower volume vehicles and adaptations of systems originally designed for the European market. Manufacturers have considered customer feedback from these early applications in the implementation of recent stop-start systems, which are now smoother and more unobtrusive to the driver. For example, some suppliers have proposed continuously engagement of the starter motor to improve the restart process. Others have implemented systems that maintain a specific piston position while stopped in order to achieve a fast and smooth restart by firing a single cylinder. As a result, improved systems promise greater effectiveness through more frequent and longer periods of idle stop time while operating in a more transparent manner.

Vehicles with sufficiently smooth and seamless stop-start technology have been well-received by consumers,[202] especially when paired with some explanation of the system's benefits and operating characteristics at the time of delivery. With these more recent implementations, it is more common now for stop-start systems to be applied as standard equipment on high-volume vehicles like the Chevrolet Malibu, Chrysler 200, Jeep Cherokee, and Ram 1500 truck. Ford also offers it on its high-selling F-150, and expects to offer it on 70 percent of its North America vehicle lineup by 2017.[203]

The Draft TAR noted that the introduction of stop-start has stimulated development of 12V battery systems capable of providing the enhanced performance and cycle life that it requires. Much of this activity has involved variations of lead-acid chemistries, such as absorbed-glass-mat (AGM) designs and lead-carbon formulations. For example, at the 2015 Advanced Automotive Battery Conference (AABC), a Planar Layered Matrix (PLM) 12V enhanced lead-acid battery was exhibited by Energy Power Systems (EPS). EPS claimed this technology increases battery power and regenerative charging capability by a factor of four while increasing the battery life by a factor of five, at a similar cost to a conventional AGM lead-acid battery.

The Draft TAR also noted that lithium-ion chemistries specially adapted for stop-start applications have begun to take hold. As one example, Maxwell Technologies has developed a 12V lithium-ion battery combined with a 395V ultra-capacitor pack designed for 12V stop-start systems.[204] The dual pack was said to provide quicker engine start, lower voltage drop, capacity and life improvement while providing capability to operate at -30 degrees Celsius. Since the battery and ultra-capacitor operate at different voltages, these systems require additional electronics for DC to DC conversion. These systems are also likely to cost more than lead-acid based systems. The cost of the Maxwell dual pack stop-start system is estimated at about $230/pack, which is higher than that of an advanced lead-acid battery. In general, use of the lithium-ion chemistry for 12V stop-start applications continues to face challenges with regard to cost as well as cold-start operation.

The Mazda i-ELOOP system[205] represents an incremental step beyond basic stop-start, using ultra capacitors to store regenerative brake energy during deceleration and coasting. While the system cannot use the reclaimed energy for propulsion, it supplements the energy used by accessories and climate control, potentially saving energy by allowing the engine to stay off for slightly longer periods.

Based on a review of these and similar industry developments, as well as data collected from other sources, EPA updated effectiveness estimates for stop-start technology in the Draft TAR and these estimates remain current for this Proposed Determination analysis. The cost and effectiveness estimates, as well as some of the public comments received on stop-start technology, are discussed further in Chapter 2.3.4.3.1.

2.2.4.4.2 *Mild Hybrids*

In this analysis, mild hybrid refers to a technology that supplements the internal combustion engine by providing limited hybridization, typically including a limited amount of electrical launch assistance, some regeneration, and stop-start capability. Together, these features reduce energy consumption by optimizing loading of the engine, enabling some engine downsizing, allowing the engine to turn off at times, and recovering a portion of the energy that would otherwise be wasted by friction braking. Mild hybrids commonly are implemented in part by replacing the standard alternator with an enhanced power, higher voltage, higher efficiency belt-driven starter-alternator which can provide some propulsion assist and also recover braking energy while the vehicle slows down (regenerative braking). Although the belt-driven basis of these systems can limit their power capability to approximately 10 kW to 15 kW,[206] mild hybrids can provide greater benefit than stop-start systems while keeping cost significantly lower than that of a strong hybrid.

Mild hybrids operate at a higher voltage than 12V stop-start systems. Even the relatively mild demands of stop-start[207] technology are very demanding on a 12V electrical system. Achieving the 10 to 15 kW demanded of a mild hybrid application at 12V would require discharge currents of 1000 Amps or more, which would require very thick, heavy, and expensive electrical conductors. In order to achieve effective launch assist and regeneration, mild hybrids therefore operate at higher voltages of 48V to 120V or higher, with an increased battery capacity as well.

The higher system voltage allows the use of a smaller, more powerful electric motor and reduces the weight of the motor, inverter, and battery wiring harnesses.

In the 2012 FRM analysis, mild hybrid technology was referred to as "higher-voltage stop-start/belt integrated starter generator (BISG)" and was limited to BISG architecture, as exemplified by the Chevrolet Malibu eAssist system. The primary source of effectiveness data used by EPA was derived from the Lumped Parameter Model based on modeling of the Malibu Eco BAS (BISG) system with a 15 kW motor and 0.5 kWh battery. EPA cost estimates were based on an analysis of this system with a 0.25 kWh battery. EPA had then assumed an absolute CO_2 effectiveness ranging from 6.8 to 8.0 percent depending on vehicle class (2012 RIA, p. 1-18). These effectiveness values included only the effectiveness related to the hybridized drivetrain (battery and electric motor) and supported accessories.

The 2012 FRM analysis had projected that mild hybrids would achieve a fleet-level penetration of 26 percent[208] in the cost-minimizing pathway for compliance with the MY2025 standards. This was reduced to 18 percent in the Draft TAR analysis.[137]

The EPA Trends Report does not distinguish between mild and strong hybrids in its accounting of hybrid vehicle penetration, which makes it difficult to separate the relative penetration of mild hybrids from that of strong hybrids since the 2012 FRM. Although most analysts had forecast the market share of hybrid vehicles to slowly but steadily rise, hybrid market share (including mild and strong hybrids) has leveled off at about 3 to 3.5 percent[209] of the total light vehicle market since 2009. According to a report by the International Council on Clean Transportation (ICCT),[210] GM mild hybrid systems accounted for about 2 percent of the 2014 U.S. market, a decline from about 5 percent in 2013. Other sources have remained optimistic that penetration levels will eventually grow substantially. For example, the automotive supplier Continental has projected market penetration rates of three million BEVs, 12 million strong hybrids and 13 million 48V mild hybrids by 2025.[211] In comments on the Draft TAR, A123 stated that it expects "sales of more than 1 million 48V battery systems annually to its global customer base by the year 2020." Mercedes-Benz has announced plans to introduce a 48V architecture, enabling mild hybrid functions, in some of its vehicles by 2017.[142] Toyota has also been a leader in and proponent of hybridization, stating for example in comments on the Draft TAR, "Continued expansion of hybrids will play a key a role in the eventual shift to greater levels of vehicle electrification."

Examples of high-voltage BISG mild hybrid systems currently present in the U.S. market are the 115V Buick Lacrosse eAssist and the 90V 2017 Chevrolet Silverado truck[218] mild hybrid system. Hyundai is also using BISG technology for torque smoothing in its high voltage BISG Hybrid Starter Generator (HSG) drivetrain.

Like stop-start technology, mild hybrid technology alters the customary operation of the engine and so can alter the traditional feel of driving. In many situations the engine may turn off less frequently and be off for longer periods, although the cycling may appear more random because it is not necessarily connected to stop and go operation. Some of the effectiveness of mild hybrids may be diminished by individual driving habits, leading to possible dissatisfaction with fuel economy. For example, the fuel economy benefit of mild hybrids may fall off more quickly with aggressive driving due to the lower potential for engine-off operation under these conditions.

The 2015 National Academy of Sciences (NAS) report estimated a 10 percent effectiveness for mild hybrid technology[212] based upon the 11 percent fuel consumption reduction observed in the 2013 GM Malibu Eco. The NAS estimate appears reasonable when considering improvements in the GM Ecotec engine and six-speed automatic transmission, and when considering differences between the vehicle's 0-60 mph acceleration times (which are reported to be about 7.8 seconds for the base 2013 Malibu LT[213] and 8.2 seconds for the 2013 Malibu Eco[214]).

The GM Malibu 15 kW 115V eAssist BISG mild hybrid improved fuel economy about 11 percent over the conventional Malibu Eco 2.5L PFI engine with a six speed transmission. This effectiveness figure includes the benefits of other non-hybrid technologies (such as low rolling resistance tires, underbody aerodynamic panels and radiator grille active shutters) that are present on the e-Assist mild hybrid package.

The 2013 GM Malibu Eco's eAssist system uses a 15 kW BISG induction motor with 11 kW launch assist during heavy acceleration and 15 kW of recuperative braking power.[215] The effectiveness of a 12 to 15 kW electric machine with a liquid-cooled integrated inverter in a 48V mild hybrid is comparable to that of a 15 kW motor in 100V+ mild hybrid when taking into consideration the 30 pound weight reduction from the battery pack and the three, long and heavy 3-phase AC cables used in the 100+V BISG system. For an equivalent mass, 48V mild hybrid technology effectiveness[216] will be slightly less than that of 100V+ mild hybrids.

Since the 2012 FRM, the GM eAssist platform has migrated to other vehicles in the GM lineup. In February 2016, General Motors announced a limited pilot program offering a version of its eAssist mild hybrid system on approximately 200 GMC Sierra 1500[217] and 500 Chevrolet Silverado[218] 2WD pickups in California. This option is offered at a retail price of $500, significantly lower than the approximately $1000 cost attributed to the 2013 Malibu Eco hybrid system by an FEV teardown analysis.[219] GM credits this system with up to a 13 percent improvement in city fuel economy. This development is significant in part because it is the first example of a BISG system applied to production pickup trucks by a major manufacturer. GM stated that it would "monitor the market closely […] and adjust as appropriate moving forward." GM is also offering the eAssist BISG mild hybrid as an option to Chevrolet Equinox and GMC Terrain midsize SUVs, and Buick Verano, Buick Regal, and Buick Lacrosse. At least one analyst expects annual sales of these vehicles to grow to about 100,000 by 2020,[209] suggesting that BISG may become a significant contributor to the compliance path of manufacturers that rely on this technology.

The Honda Civic IMA (Integrated Motor Assist) or P1 mild hybrid integrates a 1.5L inline four cylinder Atkinson cycle engine[220] with a CVT transmission and a 17 kW CISG motor to achieve a 29.7 percent total GHG effectiveness (calculated from two-cycle certification data comparing the 2015 1.5L Honda Civic IMA to the 2015 1.8L Honda Civic sedan). The effectiveness attributable to the mild hybrid technology alone can be estimated by subtracting the effectiveness of the other technologies present on the vehicle. This includes about 1.9 percent for low rolling resistance tires (LRRT1), 0.7 percent for low drag brakes (LDB), 1.3 percent for electrical power steering (EPS), 0.7 percent for LUB, 3 percent for use of Atkinson cycle ICP and DCP, 3.5 percent for use of a CVT, 3 percent for HEG, 0.8 percent aerodynamics and 1.5 percent for weight difference, resulting in about 13.3 percent GHG effectiveness for this system.

This comparison does not consider the small 0-60 acceleration performance loss (from 9 seconds to 9.8 seconds) between the standard 1.8L sedan and the IMA hybrid.

Combined two-cycle certification test data comparing the 2015 Mercedes-Benz E400 20kW120V P2 mild hybrid and the comparable E350 conventional vehicle indicated about 13 percent GHG effectiveness.

To date, most mild hybrids such as the aforementioned Malibu eAssist have been designed to operate at a voltage of 100V or higher. However, as discussed in the Draft TAR, evidence has accumulated since the 2012 FRM to suggest that many functions of a BISG mild hybrid can be provided at a lower voltage, such as 48V, at significantly reduced costs. Several attributes of 48V systems contribute to this lower cost. The voltage is lower than the 60V safety threshold that would otherwise require more robust electrical shock protection. The small power levels associated with these components promotes integration of the inverter with the motor and the elimination of long stretches of cable, further isolating the AC portion of the circuit. The relatively small 48V battery pack is significantly less costly due to having a potentially smaller capacity as well as fewer cells due to its lower voltage. The battery may not require liquid cooling, instead being passively cooled with appropriate placement and packaging. The relatively low power requirements of a 48V system also promotes use of relatively inexpensive motor technology (such as induction or switched reluctance) without as strong a concern over NVH or efficiency. The lower voltage and capacity leads to a lower return in effectiveness[216] (for example, a 48V system may have a regenerative energy capturing efficiency of about 50 percent[221] compared to perhaps 85 percent for a typical strong hybrid), but the cost reduction may make these systems more cost effective. For example, A123 Systems has projected a fuel economy effectiveness of 12 percent for a 48V mild hybrid system utilizing its 48V battery technology.[222] At this level of effectiveness, this system was described as being more cost effective (at $55 per percent fuel economy gain) than a full hybrid solution (at $83).

48V mild hybrid technology has received an increasing amount of attention since the 2012 FRM, with a number of OEMs and suppliers introducing several developmental 48V mild hybrid systems capable of significant CO_2 and fuel consumption reductions. At the 2015 SAE Hybrid and Electric Vehicle Technology Symposium, Controlled Power Technology (CPT) exhibited a switched-reluctance motor-generator technology and an electric supercharger for 48V vehicle electrification. Bosch has presented a 48V mild hybrid system scheduled to be ready for production by 2017[223] that it describes as capable of a 15 percent reduction in fuel consumption. At the 2015 Consumer Electronics Show (CES), Continental exhibited a 48V mild hybrid system which consists of a 48V Belt Integrated Starter Generator (BISG) replacing 12V alternator, DC/DC converter and a 48V lithium-ion battery pack. The BISG motor is an induction motor, and liquid cooled by engine coolant. The motor can be decoupled for downhill coasting by disconnecting the transmission from the engine. Continental expects this 48V mild hybrid system to begin production in 2016.[224] In concert with these introductions, suppliers are also predicting significant market penetration for 48V systems within the time frame of the rule. Bosch projected some 4 million 48V mild hybrid vehicles worldwide in 2020, while Eaton expected up to 3 million 48V mild hybrids globally by 2020.[210]

A 48V mild hybrid truck was announced in the recent FCA business plan[225] for the 2018 Dodge Ram 1500 large truck using next-generation powertrains.[226] Schaeffler[227] and Hyundai[228] also recently demonstrated advanced engineering prototypes of small and mid-size SUV 48V mild hybrids.

48V mild hybrid prototype demonstration vehicles from Audi, Hyundai, Mitsubishi, and Johnson Controls have been described as delivering about 10 to 15 percent CO_2 reduction and fuel economy improvement.[229] Continental, a major Tier 1 supplier of electrified automotive systems, has presented a prototype small car with a 10 kW BISG 48V mild hybrid system, said to provide a 7 percent CO_2 reduction.[230] In the FRM, the agencies calculated a 7.4 percent GHG effectiveness for small cars equipped with a 10 kW BISG mild hybrid system, which is comparable to the Continental results.

Industry appears to be coalescing on a 48V standard for such mid-voltage hybrid applications, with manufacturers such as Audi, BMW, Daimler, Porsche and VW having initiated a 48V standard known as LV148.[231]

48V mild hybrid technology can also be understood as an alternative to stop-start that is not as costly as adopting a higher voltage mild hybrid technology. Compared to 12V stop-start, 48V mild hybrids provide several benefits for a relatively small cost increase,[232] such as faster engine starting, more engine-off time, significant regenerative braking capacity, and better electrical support for accessories while the engine is off. In comments on the Draft TAR, several commenters reiterated the conclusion that 48V technology is more cost effective than higher voltage systems. For example, A123 commented, "we expect 48V mild hybrids to remain one of the most cost effective forms of electrification through model year 2025 and beyond."

As discussed in the Draft TAR, EPA expects 48V mild hybrid technology to become increasingly common and relied upon as a GHG reducing technology. See generally Draft TAR at 5-77 and Chapter 5.2.4.3.2. EPA therefore added the 48V mild hybrid architecture to the Draft TAR analysis and will retain it as part of this Proposed Determination analysis.

Recent developments in the 48V platform have suggested that it is also capable of pushing the limits of what would be considered a mild hybrid. New P2, P2/P4 and P0/P4 48V system architectures have been presented by various suppliers such as Bosch, Schaeffler, Continental, and Control Power Technologies, ranging from 20 kW to 45 kW of assist capability.[211] The effectiveness for these new, more powerful systems, particularly those on the higher end of the power range (30-45kW) may approach that of P2 strong hybrids but at a much lower cost. For example, Bosch has presented a 2nd generation, 48V P2-architecture mild hybrid currently in development.[233] In this 48V P2 system, a more powerful motor-generator is integrated into the transmission (to create a transmission-integrated starter-generator or TISG architecture). As with a P2 strong hybrid, the motor can be decoupled from the engine to propel the vehicle in an electric-drive mode in stop-and-go traffic and for short distances.

Transcending the BISG format provides a way around common mild hybrid limitations, such as the 15 kW peak motor power limit, belt efficiency losses, and tandem operation of the engine with the motor. Stronger formats such as Crank-Integrated Starter Generator (CISG) P1 architecture, as well as Transmission Integrated Starter Generator (TISG) P2 architecture, overcome the peak motor power limitation in BISG P0 mild hybrids and further increase the potential effectiveness of mild hybrid technology. The Honda IMA CISG P1 mild hybrid system cannot run the electric motor alone without simultaneously operating the internal combustion engine,[234] while the TISG P2 mild hybrid format allows the engine shut down while the electric motor works independently for braking energy recuperation and vehicle propulsion. The effectiveness of TISG P2 mild hybrids therefore may have higher effectiveness potential than that of CISG P1 mild hybrids.

The effectiveness of TISG P2 mild hybrids appears to be higher than that of CISG P1 mild hybrids. GETRAG projected about 15 percent effectiveness for a 48V 21 kW TISG P2 mild hybrid at the 14th VDI Congress.[206] This system employs a 7 speed dual clutch hybrid transmission, which integrates one common oil circuit for cooling and lubrication, and a combined e-machine and inverter applicable not only to the 48V 21 kW mild hybrid but also to other variants such as a 220V+, 50 kW strong hybrid and a 360V+, 110 kW plug-in hybrid application. This hybrid transmission also supports other efficiency-enhancing features such as pure electric driving, extended sailing, more efficient launch assist and brake energy recuperation, battery charging when the vehicle is standing, and generator-mode/load shift; features very similar to those provided by strong hybrids.

In addition to its own benefits, mild hybridization may help enable the use of other technologies that can further improve efficiency. For example, fuel consumption reduction may approach 20 percent when an electric supercharger is used in 48V mild hybrids combined with regenerative braking energy recovery, engine downsizing and downspeeding.[235] Audi is expected to market a system utilizing this technology in 2017. As another example, a 48V, 7 kW electric supercharger[236] has been shown to deliver an extra 40 to 70 kW at the crankshaft by boosting the engine combustion process. Hence, the electric supercharger may be an effective accompaniment to engine downsizing and downspeeding.

Based on a review of these and similar industry developments, as well as data collected from other sources, EPA updated effectiveness estimates for mild hybrid technology in the Draft TAR. EPA has reviewed these estimates and finds that they remain applicable to this Proposed Determination analysis. Cost and effectiveness estimates, as well as some public comments received on this technology, are discussed further in Chapter 2.3.4.3.2.

2.2.4.4.3 *Strong Hybrids*

In this analysis, strong hybrid refers to hybrid technologies that have higher power capability and larger battery capacity than mild hybrids, thus providing for more effective management of power from the internal combustion engine, greater levels of regenerative braking, and more powerful electric propulsion capable of accelerating the vehicle with less (if any) assistance from the engine. Strong hybrids provide greater effectiveness than mild hybrids by better optimizing loading of the engine, allowing additional engine downsizing, allowing the engine to turn off for longer periods, and recovering a greater portion of braking energy. These enhanced functions tend to require higher voltages (as high as 300V to 400V) and more powerful batteries with greater energy capacity, typically on the order of 1 to 2 kWh. These attributes add to complexity due in part to safety requirements associated with higher voltages and greater battery capacity. Although strong hybrids are more expensive than mild hybrids, they can access a greater degree of fuel economy and CO_2 reduction than mild hybrids, and include some of the highest fuel economy vehicles currently in production.

Strong hybrids include several distinct architectures. On a sales-weighted basis, the power-split hybrid electric vehicle (PSHEV) represents the most common architecture, largely by virtue of its use for many years in the Toyota Prius hybrid. This system replaces the traditional transmission with a single planetary gearset and two motor/generators. The smaller motor/generator uses the engine to either charge the battery or supply additional power to the drive motor. The second, more powerful motor/generator is permanently connected to the vehicle's final drive and always turns with the wheels, as well as providing regenerative braking capability. The planetary gearset splits engine power between the first motor/generator and the output shaft to either charge the battery or supply power to the wheels.

The two-mode hybrid electric vehicle (2MHEV) is a hybrid electric drive system that uses an adaptation of a conventional stepped-ratio automatic transmission by replacing some of the transmission clutches with two electric motors that control the ratio of engine speed to vehicle speed, while clutches allow the motors to be bypassed. Although the added mechanical elements can introduce their own losses, in many cases the system overall can improve the transmission torque capacity for heavy-duty applications while possibly reducing fuel consumption and CO_2 emissions at highway speeds relative to other types of hybrid electric drive systems.

The P2 hybrid is a hybrid technology that uses a transmission integrated electric motor placed between the engine and a gearbox or transmission, with a wet or dry separation clutch which is used to decouple the motor/transmission from the engine. A P2 hybrid would typically be equipped with a larger electric machine than a mild hybrid system but smaller than a power-split or 2-mode hybrid architecture. Disengaging the clutch allows all-electric operation and more efficient brake-energy recovery. Engaging the clutch allows efficient coupling of the engine and electric motor. Based on simulation, when combined with a DCT transmission, the P2 hybrid architecture provides similar or improved fuel efficiency to other strong hybrid systems with reduced cost.

In the 2012 FRM, P2 hybrid was the only hybrid architecture that was applied in the agencies' analysis. Although PSHEV and 2MHEV technology were discussed because they were present in the market at the time of the FRM, they were not included in the analysis because the industry was expected to trend toward more cost-effective hybrid configurations such as P2.

Going back to the 2012 FRM, the primary reference EPA used for strong hybrid effectiveness was the Ricardo modeling study, which modeled a P2 with a futured DCT. On this basis EPA had estimated an absolute CO_2 effectiveness for P2 strong hybrids ranging from 13.4 to 15.7 percent depending on vehicle class (see 2012 RIA, p. 1-18). These figures included only the effectiveness related to the hybridized drivetrain (battery and electric motor) and supported accessories, and did not include the effect of any accompanying advanced engine technologies. The quoted figures were based on electric motor sizes assumed in the Ricardo vehicle simulation results and would vary with other motor sizes.

On this basis, EPA had projected that strong hybrids would achieve a fleet-level penetration of about 5 percent[237] in the cost-minimizing pathway for compliance with the MY2025 GHG standards. The Draft TAR analysis revised this to less than 3 percent.[148]

The EPA Trends Report does not distinguish between mild and strong hybrids, nor specific architectures of strong hybrids, in its accounting of hybrid vehicle penetration. Therefore it is difficult to use this source to assess the relative penetration of P2 and other strong hybrid architectures since the 2012 FRM. However, it is expected that strong hybrids are making up the majority of the market.

A recent report by the International Council on Clean Transportation (ICCT)[210] reviews market penetrations for various hybrid architectures. According to this report, the market share of the P2 hybrid architecture among all hybrids has been relatively small, having grown from about 9 percent in 2013 to about 12 percent in 2014. Toyota has continued to lead the U.S. hybrid market with 66 percent of U.S. hybrid sales in 2014. These sales largely account for the dominance of power-split hybrids in the market. In the same year, Ford claimed a 14 percent share of the U.S. hybrid market, also with power-split hybrids. P2 hybrids are primarily represented in the U.S. market by Hyundai/Kia and Honda, with 8 percent of total 2014 hybrid sales. The Honda integrated-motor-assist (IMA) architecture represented only 3 percent of the 2014 hybrid market, and is expected to be replaced by a P2 system in the near future.

Compared to the more mature, fourth generation power split hybrid architectures of Toyota and Ford, EPA believes the P2 hybrid architecture is still in a relatively early stage of development and has yet to be fully optimized. Manufacturers are continuing to make strides toward improving this architecture in recently introduced models by refining power electronics and component efficiency and integrating parts. For example, Hyundai has improved the 2nd generation Sonata hybrid by fully integrating a 38 kW traction motor and all of the other hybrid powertrain components within the transmission. The reduced weight has led to improved fuel economy with reduced costs, as evidenced by the observation that there is no major difference in effectiveness between this P2 vehicle and the 2015 Toyota Camry power-split hybrid. Going forward, similar opportunities for major cost reduction and fuel economy improvement are likely to arise in competing P2 hybrid systems.

Differences in configuration account for some of the cost and effectiveness differences between P2 and power-split architectures. The input power-split architecture requires two motors, which consist of a small generator and a bigger traction motor which drives through a simple power-split planetary gear set. The P2 architecture uses a single, smaller traction motor, but drives through a more complex conventional transmission gearing. The Honda two-motor architecture does not use a power-split planetary gear set, and therefore requires a bigger motor to directly transmit power to the drive axle compared to the typical input power-split hybrid system. For example, the Honda Accord 2-motor hybrid uses a 124 kW traction motor[238] while the Toyota Camry power-split hybrid uses a 105 kW traction motor.[239] Highly efficient motor-integrated DCT transmissions have recently entered production or are under development and are being adopted in the latest P2 parallel hybrid designs. The architecture of the P2 parallel hybrid also may potentially provide for a greater towing capacity than the power-split hybrid architecture, which in the current production market appears to be limited to the 3500-lbtowing capacity of the Toyota Highlander hybrid.

Even the relatively well-developed power-split architecture continues to show room for efficiency improvements. Toyota redesigned the 2016 Prius[240] transaxle and motor in its fourth generation Hybrid Synergy Drive (HSD) to reduce combined weight by 6 percent and volume by 12 percent. The planetary gear arrangement in the reduction gear has been replaced with parallel gears, reducing mechanical losses by approximately 20 percent. The 53 kW main traction motor is mounted on a parallel shaft, enabling the transmission case volume to be reduced substantially while also reducing frictional losses by about 20 percent. The power control unit, which combines the controller, inverter and DC/DC converter, was attached to the top of the transaxle and its size reduced by about 33 percent by eliminating several high-voltage cables. The lithium-ion battery pack, initially made available on the 'Eco' trim level, is 6 percent smaller and 31 percent lighter than the nickel-metal hydride (Ni-MH) version, while providing the same power output and degree of hybridization.

Further evidence that the effectiveness of input power-split hybrids and P2 parallel hybrids are getting closer is shown by the 2017 Hyundai IONIQ P2 hybrid, announced in 2016. The combined fuel economy of this vehicle, with the GEN2 Hyundai P2 parallel hybrid drive, is expected to be about 53 mpg, which is comparable to the 56 mpg fuel economy of the 2016 GEN4 Toyota Prius Eco hybrid. This vehicle also employs advanced technologies such as a gasoline direct injection (GDI) inline 4 cylinder Atkinson cycle engine, cooled EGR, CVVT, dual circuit cooling system, 6 speed dual clutch transmission (DCT), exhaust heat recovery system, and an intake oil control valve, which act together to increase engine thermal efficiency to as high as 40 percent.

As reported by ICCT[210] (and reproduced here in Figure 2.30), the estimated costs for hybrid systems have tended to decline steadily in the years after their introduction. If these trends continue, significant reductions in hybrid system cost may be expected during the time frame of the rule.

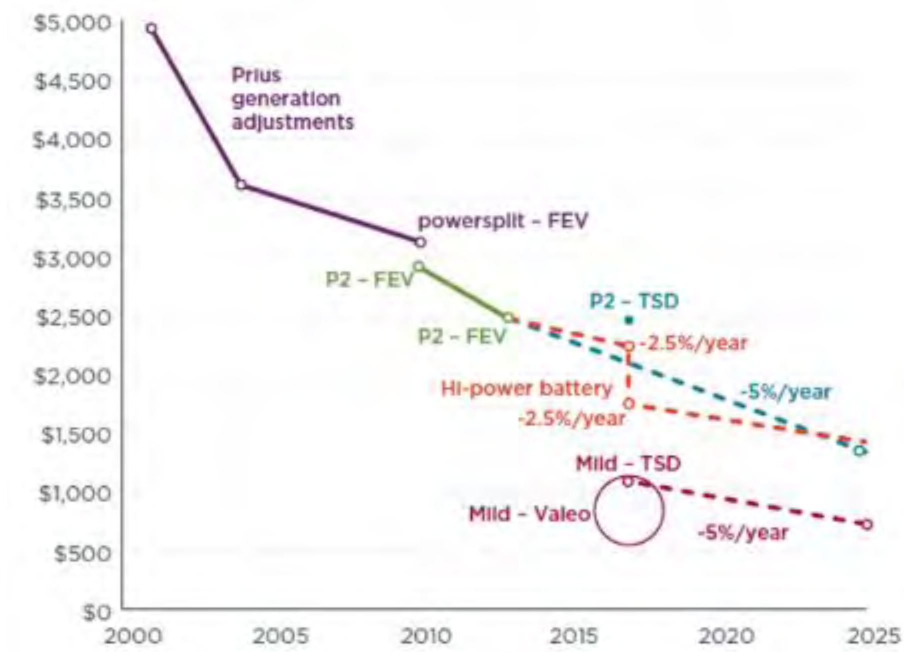


Figure 2.30 Hybrid System Direct Manufacturing Cost Projection (ICCT, 2015)

The overall cost of power-split, P2 and two-motor hybrid systems appear to be comparable. For example, as estimated by an FEV teardown in 2010,[241] the reported power-split hybrid cost of $2,565[242] was only slightly higher than the $2,392 cost estimate for a P2 hybrid system. As discussed in the Draft TAR, EPA therefore combined all strong hybrid architectures under the strong hybrid category and continues to do so for this Proposed Determination analysis. Several public comments received on the Draft TAR addressed this decision to model strong hybrids with the same cost and effectiveness without regard to specific architecture. These comments, as well as other comments considered in determining cost and effectiveness for strong hybrid technology, are addressed in Chapter 2.3.4.3 (Cost and Effectiveness for Strong Hybrids).

For the Draft TAR, EPA significantly updated cost and effectiveness estimates for strong hybrid technology. On consideration of the availability of any significant new information and consideration of public comments, EPA continues to believe these estimates are appropriate to use for this Proposed Determination analysis, as discussed in Chapter 2.3.4.3.3.

2.2.4.4.4 Plug-in Hybrids

A plug-in hybrid electric vehicle (PHEV) is much like a hybrid electric vehicle, but with at least three significant functional differences. The first is the addition of a means to charge the battery pack from an outside source of electricity (usually the electric grid). Second, a PHEV has a much larger battery capacity, and often a greater usable fraction as well. Finally, it has a control system that allows the battery to be significantly depleted during normal operation.

Deriving some of their propulsion energy from the electric grid provides several advantages for PHEVs. PHEVs offer a significant opportunity to replace petroleum used for transportation energy with domestically-produced electricity. The reduction in petroleum usage does, of course, depend on the amount of electric drive the vehicle is capable of providing under its duty cycle. PHEVs also provide electric utilities the possibility to increase electric generation during off-peak periods overnight when there is excess generation capacity and electricity prices are lower. Utilities like to increase this base load because it increases overall system efficiency and lowers average costs. PHEVs can lower localized emissions of criteria pollutants and air toxics especially in urban areas by operating on electric power. The emissions from the power generation occur outside the urban area at the power generation plant which provides health benefits for residents of the more densely populated urban areas by moving emissions of ozone precursors out of the urban air shed. Unlike most other alternative fuel technologies, PHEVs can initially use an existing infrastructure for refueling (charging and liquid refueling) so investments in infrastructure may be reduced.

Depending on the operating strategy chosen by the manufacturer, a PHEV either provides for a significant all-electric range (AER) during which the engine does not operate, or provides for blended operation in which the engine provides some of the propulsion energy while the battery contributes the remainder. In this discussion, the former is referred to as a PHEV with AER, and the latter is referred to as a blended PHEV.

EPA models PHEVs in two configurations, designated PHEV20 and PHEV40 (having 20 miles and 40 miles, respectively, of all-electric range or its equivalent). Range is modeled as an approximate real-world range comparable to an EPA label range (specifically, 70 percent of a projected two-cycle range).

For GHG analysis purposes, PHEVs are assigned an effectiveness derived from the SAE J1711 recommended procedure for accounting for utility factor (the balance between miles traveled on electricity in all-electric mode and other miles powered by fuel). On this basis, in the 2012 FRM and the Draft TAR, PHEV20 was assigned an absolute CO_2 effectiveness of 40 percent, and PHEV40 was assigned 63 percent (see 2012 RIA, p. 1-18).

In the Draft TAR analysis, the cost-minimizing pathway for compliance with the MY2025 standards projected a very low fleet-level penetration of PHEVs (less than 2 percent).[148,W]

At the outset of the rule, only a few PHEVs were commercially available in the U.S. market. The most prominent examples were the Chevy Volt and the Fisker Karma, both of which debuted as MY2011 vehicles, and the 2012 Toyota Prius Plug-In Hybrid. Production of the Karma was discontinued in late 2012 as Fisker encountered financial difficulties. Fisker was sold to the Chinese company Wanxiang Group, and renamed to Karma, but has not resumed significant production to date.

Even these early PHEVs demonstrated important differences in their operating strategy that remain visible in today's market. The Chevy Volt and Fisker Karma both offered a significant AER by including a distinct charge-depleting mode in its operating strategy. In contrast, the Toyota Prius Plug-In utilized a more blended mode of operation in which the engine could regularly operate during the charge depletion stage depending on driving conditions, for example, if the vehicle exceeded a certain speed or power demand. Both strategies continue to appear in the market today, with some vehicles emphasizing AER and others emphasizing overall fuel economy in blended operation. Some PHEVs that employ blended operation are able to achieve an all-electric range during EPA city and highway test cycles, but may operate in blended mode (using a combination of gasoline and electricity) when driven more aggressively. Operation in blended mode may be converted to an equivalent AER by applying a utility factor that considers the contribution of stored electricity to the total distance traveled in this mode. Both types of PHEVs are therefore capable of displacing conventionally-fueled mileage with electrically fueled mileage.

The 2011 Chevy Volt had an EPA-rated AER of 38 miles, while that of the Fisker Karma was 32 miles. The Prius was rated at 6 miles AER (11 miles including blended mode). The market has since expanded to include many additional products. Table 2.2 shows a summary of PHEV models that are in current production or have been available during the period since the FRM.

Table 2.2 Trends in EPA-Estimated Range of PHEVs

	EPA range (mi)					
PHEV model	2012	2013	2014	2015	2016	2017
Chevy Volt	35	38	38	38	53	53
Fisker Karma	33	-	-	-	-	-
Toyota Prius Plug-In Hybrid	11	11	11	11	NL	**
Ford Fusion Energi	-	20	20	20	20	22
Ford C-Max Energi	-	20	20	20	20	**
Honda Accord PHV	-	-	13	-	-	-
McLaren P1	-	-	19	19	-	-
BMW i3 Rex	-	-	72	72	72	97
BMW i8	-	-	15	15	15	15
Cadillac ELR	-	-	37	37	40	**
Cadillac ELR Sport	-	-	-	-	36	**
Porsche Panamera S E-Hybrid	-	-	16	16	16	14

[W] Because vehicles attributed to the ZEV program were included as part of the EPA reference case, absolute penetration of PHEVs would be greater.

Porsche 918 Spyder	-	-	-	12	-	-
Mercedes-Benz S550e	-	-	-	14	14	**
BMW X5 xDrive40e	-	-	-	NA	14	14
Porsche Cayenne S e-Hybrid	-	-	-	14	14	**
Hyundai Sonata PHEV	-	-	-	-	27	27
Mercedes-Benz C350e	-	-	-	-	18.6*	**
Audi A3 e-tron	-	-	-	-	16	16
Audi A3 e-tron ultra					17	**
BMW 330e	-	-	-	-	14	14
Mercedes-Benz GLE 550e 4MATIC	-	-	-	-	12	
Volvo XC90 T8 Hybrid	-	-	-	-	14	14
BMW 740e xDrive	-	-	-	-	-	14

Notes:
NL = vehicle not listed in Fuel Economy Guide
NA = rating not available in Fuel Economy Guide
* approximated from press or manufacturer estimate
** Not yet listed in 2017 Fuel Economy Guide at time of writing

The growth in PHEV models as evidenced in Table 2.2 has likely been driven in part by manufacturers considering PHEVs as part of their pathway for compliance with the 2017-2025 standards, but even more so by California's zero emission vehicle (ZEV) program. In 2012, CARB adopted increased requirements for ZEVs and PHEVs through MY2025, and nine additional states have adopted the ZEV program. A 2015 National Academy of Science report on PEV deployment[243] cites the California ZEV regulation as being particularly influential in increasing PEV production and adoption.

In addition, PHEVs from all manufacturers continue to be eligible for a federal tax credit of up to $7,500, effectively reducing their net cost to consumers.[244, 245] This credit applies to the first 200,000 PEVs (PHEVs and BEVs combined) that are produced by a given manufacturer and gradually phases out thereafter. While most manufacturers are unlikely to approach this limit for at least several years, some of the leading PEV manufacturers such as General Motors, Nissan, and Tesla are making steady progress toward the limit. For example, if the Gen2 Chevy Volt sells well, and the recently introduced Chevy Bolt EV does also, it is possible that General Motors could reach the limit by sometime in 2018. Strong future sales of the Tesla Model X and Model 3, or the anticipated 200-mile version of the Nissan Leaf, could cause Tesla and Nissan to approach the limit in a similar time frame.[246] Although reaching the limit does not immediately discontinue the incentive, which would continue to be applicable to additional sales until the second calendar quarter after it is exceeded, the amount of the credit phases out rapidly over the following year. However, in addition to federal incentives, many states including California and the states that have adopted California's ZEV program offer incentives at the state and local levels.

It is important to note that most PHEVs are built on global platforms, meaning that economies of scale for the U.S. market may be driven in part by incentives in other countries. Incentives for PHEVs in the European Union and China are particularly notable because many manufacturers that serve the U.S. also serve these markets.

Trends in PHEV Electric Range

The electric range of a PHEV (either AER or equivalent AER) is largely a function of the provided battery capacity. Figure 2.31 shows the relationship between the battery capacity of production PHEVs and their EPA-estimated electric driving range (or the best estimate available at writing).

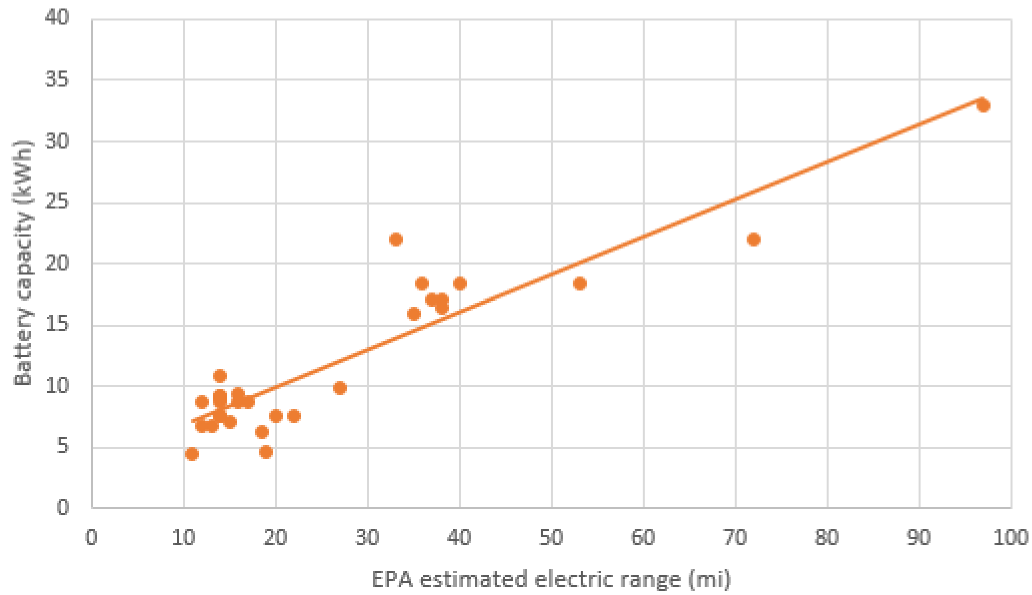


Figure 2.31 Battery Gross Capacity and Estimated AER or Equivalent for MY2012-2017 PHEVs[X]

As the Table and Figure shows, PHEV electric range varies considerably among models. Among the 2012-2016 PHEVs depicted, two distinct clusters appear, one consisting of longer-range PHEVs with AER in the vicinity of 35 to 40 miles, and another consisting of shorter-range vehicles offering between 10 and 20 miles of range (either AER or its equivalent in blended operation). Some longer-range examples are scattered between 53 and 97 miles AER.

The 35-to-40 mile cluster consists of various versions of the Chevy Volt and Cadillac ELR (which shares the Voltec powertrain), and the discontinued Fisker Karma (at 33 miles). The longer-range examples consist of the 2016 Volt (at 53 miles) and two versions of the BMW i3 Rex (at 72 miles and 97 miles). These are all PHEVs with AER that can provide a true all-electric drive mode under a wide range of operation. These PHEVs require a larger battery capacity than 10-to-20 mile PHEVs, which tends to increase their purchase price relative to the latter.

The shorter-range cluster includes several blended-operation PHEVs. With the exception of the Toyota Prius PHV (11 miles) and the Ford Energi models (20 miles), these emerged primarily in the 2015 and 2016 MYs from OEMs that tend to specialize in luxury or high-performance vehicles. This suggests that these OEMs are considering PHEVs as a compliance strategy, as projected in the FRM. For example, when BMW announced the U.S. versions of the 330e and the X5 xDrive40e PHEVs in November 2015, BMW Product Manager Jose Guerrero was quoted as saying that the timing of introductions such as these "wasn't a competitive impulse by any manufacturer … it was an internal impulse that we know that in the future our cars need

[X] Range figures gathered from 2012-2017 EPA Fuel Economy Guides.

to be more efficient, and this is a way … into that efficiency."[247] The Mitsubishi Outlander PHEV, expected to enter the U.S. market in 2017[248] after several delays,[249] is also expected to have an EPA AER in the neighborhood of 20 miles. These and similar announcements suggest that a distinct segment of PHEV20-type vehicles is likely to continue in the future as manufacturers continue to select this lower cost pathway.

Where new generations of the same model have been announced, the range has in some cases been increased. For example, the AER of the Chevy Volt has increased from 38 miles to 53 miles. Going forward, several OEMs have indicated that second generation PHEV products will have more AER and more electric power capability, by targeting US06 capability, with minimal if any reliance on the engine and 30 miles or more of AER. For example, the FCA Pacifica plug-in minivan was announced in January 2016 as targeting a 30 mile all-electric range, with capability to operate all-electric over most operating conditions.[250] Honda is reported to be considering a 40 mile AER for an upcoming PHEV that would replace the now-discontinued Honda Accord PHV, which had an AER of only 13 miles.[251] Similarly, other manufacturers including Toyota, GM, and Ford have suggested that their 2017 to 2018 PHEV products will be targeting at least 30 miles of electric range.

In such announcements, manufacturers have frequently cited customer desire for an all-electric driving experience. As one example, GM appears to credit consumer demand for more range as part of the impetus for increasing the range of the 2016 Volt. According to Chief Engineer Andrew Farah, "We listened to our customers … they were very clear when they told us that they wanted more range."[252] These manufacturers appear to be responding by increasing the potential for all-electric operation by increasing electric powertrain power ratings and battery capacity.

The California Zero-Emission Vehicle (ZEV) program also may be influencing PHEV range. To qualify as transitional-zero emission vehicles (TZEVs) under the program, PHEVs must provide at least 10 miles of AER operation on the UDDS drive schedule (as well as meet certain criteria pollutant standards).[253] Since many PHEV manufacturers market in ZEV states as well as other states, the ZEV program provides a strong incentive for producing PHEVs with AERs above this threshold.

Other incentive programs may be encouraging longer PHEV electric range. One example is the China New Energy Vehicles Program.[254] Renewal of this program in 2013 increased the eligibility requirements for PHEVs to a minimum 50 km (30 mile) AER (under the NEDC cycle) in order to qualify for purchase subsidies.[255] There is some evidence that this may be encouraging manufacturers of global-market PHEVs to increase AER to at least this level.[256] For example, the Cadillac CT6 PHEV was announced in April 2015 at the Shanghai Auto Show, where it was described as qualifying for the New Energy Vehicles incentives with a range in excess of 60 km (37 miles).[257] The U.S. version will have the same 18.4 kWh battery pack as the China version, suggesting that its AER will be similar. As of July 2016, at least one local U.S. incentive in the state of Washington will also adopt a 30-mile PHEV range requirement to qualify for a sales tax exemption up to $3,100.[258]

Manufacturers have continued to pursue and implement improvements in the efficiency and cost of battery and non-battery components for PHEVs. One example is the 2016 Chevy Volt, in which the weight of the battery pack was reduced by 14 kg despite an increase in its capacity from 17.1 kWh to 18.4 kWh. The weight of the traction motor was also reduced by 45 kg, and additional weight and cost were saved by integrating the inverter with the motor and eliminating long runs of high voltage electrical cable.[162,163]

Improvements in component efficiency and road load have both improved performance of production PHEVs. For example, GM has indicated that the 2016 Chevy Volt improved its average electric powertrain efficiency over the EPA city and highway cycles by 3 percentage points (or 4 percent absolute) compared to the first generation Volt, improving from 86 percent to 89 percent for the city, and from 84 percent to 87 percent for the highway. Drive unit losses (including losses of the electric motor, inverter, and transmission) were reduced by 39 percent in the city cycle and by 35 percent in the highway cycle.[259] The Gen2 Volt also provides a good example of the use of standard road load improvements to increase range in a PHEV.[178] Here, significant changes to the electric propulsion system were accompanied by improvements in brake drag, reductions in accessory load, and significant improvement of vehicle mass efficiency.

In both the 2012 FRM analysis and the Draft TAR analysis, EPA envisioned PHEV20 and PHEV40 as representative of PHEVs that are likely to play a significant role in achieving fleet compliance during the time frame of the rule. As Figure 2.31 shows, PHEV20 continues to be represented in the market by several 20-mile and shorter range PHEVs. PHEV40 is also represented by several vehicles, primarily earlier versions of the Chevy Volt and Cadillac ELR. PHEV40 has also been surpassed in real-world range by the 2016 Chevy Volt at 53 miles, and by the BMW i3, which with its range extender option becomes classified as a PHEV with either 72 or 97 miles AER, depending on configuration.

As discussed in the Draft TAR, EPA considered replacing PHEV40 with a longer range, such as PHEV50, but ultimately decided not to do so based on an examination of PHEVs in the market. Although the 2016 Chevy Volt has now exceeded PHEV40, other production PHEVs such as the Cadillac ELR and CT6 continue to fall on the lower side of this line. The BMW i3 examples at 72 and 97 miles fall far beyond PHEV40 but at this time are not accompanied by other examples that would suggest a wider trend toward increasingly long PHEV ranges. The i3 design is also unique in having a particularly small gasoline-only range, motivated at least in part by California regulations that apply to gasoline-powered range in PHEVs. At this time, EPA believes that PHEV20 and PHEV40 continue to serve as appropriate modeling constructs for the Proposed Determination analysis.

<u>Trends in PHEV Motor Sizing</u>

In addition to driving range, the electric motor power of PHEVs is another important input to the projection of battery and system costs for PHEVs. Accurately assigning motor power is important on several fronts. First, the motor power rating has a direct effect on the battery power rating, which determines its power-to-energy (P/E) ratio and its cost. Second, the EPA battery sizing methodology accounts for the weight of the propulsion motor and power electronics as a function of rated motor power. An accurate determination of motor power rating is therefore quite critical. An accurate accounting of motor cost also requires an accurate accounting of motor power because EPA estimates PHEV motor cost as a function of peak power output.[Y]

[Y] For more discussion of the decision to scale motor cost to power output, see Chapter 2.3.4.3.6 (Cost of Non-Battery Components for xEVs).

In the Draft TAR analysis, a significant change was made to the way motor power for PHEVs was originally assigned in the 2012 FRM. Originally in the FRM analysis, PHEVs of a given vehicle class (Small car, Large car, etc.) were assigned an electric motor power rating (in kW) that would preserve the same engine-power-to-weight ratio that was observed in baseline conventional vehicles of that class. This method assumed that the all-electric acceleration of PHEVs relates to the power rating of the electric motor in the same way that the engine-powered acceleration of conventional vehicles relates to the power rating of the engine. However, as discussed in the Draft TAR, electric motors differ markedly from combustion engines, particularly in their delivery of low-speed torque. Electric motors deliver maximum torque at the lowest end of their speed range, while combustion engines must develop significant speed to deliver a comparable torque. This strong low-end torque allows electric-drive vehicles to deliver high acceleration at low speeds. This might allow a PHEV or BEV to deliver acceleration performance similar to that of a conventional vehicle but with a significantly lower nominal motor power rating than a comparably performing combustion engine. A new sizing method, based on an empirical survey of PHEV performance, was therefore developed and described in the Draft TAR analysis.

As discussed in the Draft TAR, a number of production PHEVs have now been offered on the market, providing a significant sample size to allow some observations to be drawn regarding the necessary motor power to provide customary performance. Accordingly, the Draft TAR found that the 2012 FRM did in fact project significantly higher PHEV motor power ratings than the majority of PHEV manufacturers subsequently specified in their MY2012-2016 products. Part of this effect was attributed to the significant presence of blended-operation PHEVs in the market, which do not require as large a motor power output as the non-blended PHEV20s that were modeled for the 2012 FRM analysis. However, the Draft TAR noted that this alone would not account for the difference because many of the 2012 FRM estimates also over predicted the motor power of non-blended PHEV40s with AER.

Accordingly, EPA significantly revised its PHEV motor power ratings for the Draft TAR analysis. PHEV20 was modeled under a blended-operation architecture which significantly reduced nominal power ratings, which were assigned at 50 percent of the total rated power of the vehicle. For non-blended PHEV40, an empirical equation was derived based on the relationship between 0-60 mi/hr acceleration time and electric motor power observed in MY2012-2016 PEVs.

Assigning a more accurate power rating to the PHEV motor provides for greater fidelity in the projected cost of both the battery and non-battery components of PHEVs. More detail on the way PHEV battery and non-battery components were sized in the Draft TAR and revised for this Proposed Determination analysis are discussed in Chapters 2.2.4.4.6 (Relating Power to Acceleration Performance) and 2.3.4.3.7 (Cost of Batteries for xEVs).

Trends in PHEV Battery Sizing

Accurately assigning battery capacity to PHEVs is also important. To assess the fidelity of the EPA battery sizing methodology, the Draft TAR compared the 2012 FRM projections of PHEV battery capacity and range to the PHEVs that entered the market during MYs 2012-2016.

Figure 2.32 compares the battery capacities of MY2012-2016 PHEVs to the battery capacities that were estimated for the Draft TAR analysis.

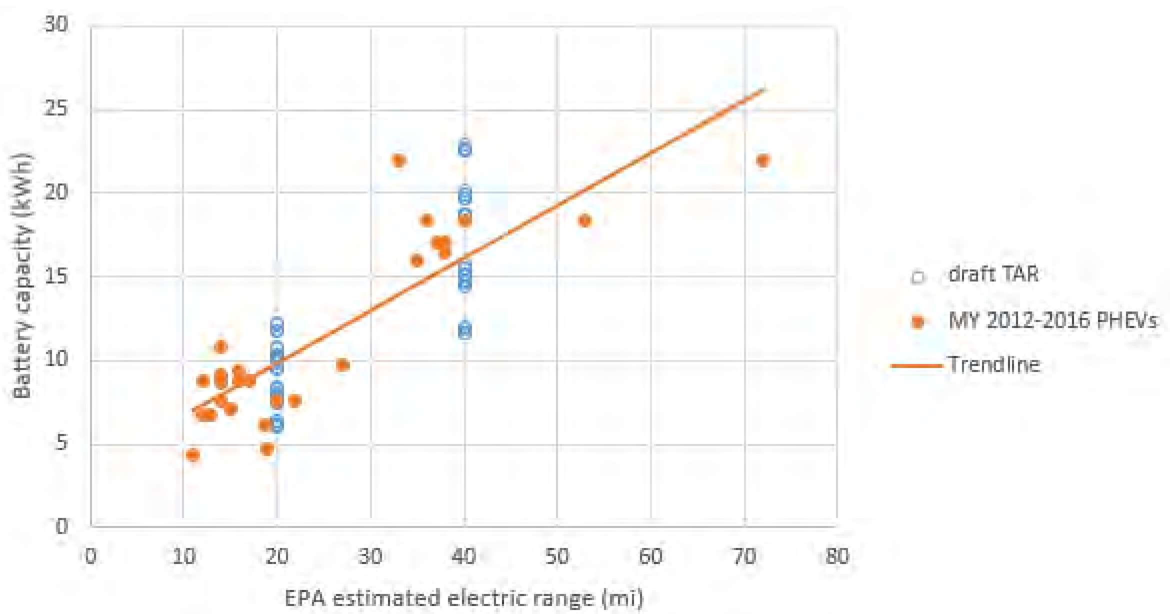


Figure 2.32 Comparison of MY2012-2016 PHEV Battery Capacities to Draft TAR Estimates

For each PHEV range (20 and 40 miles), the Figure shows the battery capacity estimates generated for the Draft TAR, corresponding to each of the vehicle classes (Small Car, Standard Car, Large Car, etc.) and several target curb weight reductions (ranging from 0 percent to 20 percent).

It can be seen from the plot that the Draft TAR estimates lined up quite well with the population of production vehicles of a similar range. This represented a significant improvement over the 2012 FRM projections, which had significantly overestimated capacities. As discussed in the Draft TAR, the improvement was a result of updating many of the parameters that are influential to the estimation of battery capacity, as described in Chapter 5.3 of the Draft TAR. This Proposed Determination analysis makes additional adjustments to the PHEV battery sizing methodology which are discussed in Chapter 2.3.4.3.7.

2.2.4.4.5 Battery Electric Vehicles

Battery electric vehicles (BEVs) are vehicles with all-electric drive powered by batteries charged from an outside source of electricity (usually the electric grid). The 2012 FRM analysis modeled three BEV configurations, designated BEV75, BEV100 and BEV150 (having 75, 100, and 150 miles range, respectively).[Z,AA] BEV150 was updated to BEV200 for the Draft TAR

[Z] As with PHEVs, the indicated range was meant to represent an approximate real-world range comparable to an EPA label range (specifically, 70 percent of a projected two-cycle range).

[AA] In the 2012 FRM and the Draft TAR, BEV75/100/200 were referred to as EV75/100/200.

analysis. Both the 2012 FRM and Draft TAR analyses predicted a very low fleet-level penetration of BEVs at about 2 percent or less.[260,BB]

As the Draft TAR found, the BEV market has grown considerably since the time of the 2012 FRM. At that time, only a few BEV models had become commercially available in the U.S. market. The most prominent examples were the 2011-12 Nissan Leaf and the Tesla Roadster, which were available nationwide. A few other BEVs were available in 2012 to very limited markets or through demonstration programs, such as the BMW Mini E and Toyota RAV4 EV. Production of the Tesla Roadster was discontinued in early 2012 but was soon replaced by the Tesla Model S. Other BEVs available near the time of the 2012 FRM were the Mitsubishi i-MiEV, BYD e6, Coda Sedan, and Ford Focus Electric.

These early BEVs were designed for different market segments, and showed significantly different philosophies on the matters of performance and driving range. Most, such as the Leaf and Mini E, were designed as moderate-performance vehicles with a driving range of 100 miles or less, seen as best suited to driving in urban areas. In contrast, the Tesla Roadster was designed for a premium, high-performance market segment at a much higher price, allowing it to offer a much longer range (245 miles by EPA estimate). Subsequent Tesla vehicles have continued to pursue similarly aggressive range and performance targets at relatively high purchase prices, while several other manufacturers continue to define a distinct segment targeting shorter ranges and moderate performance at lower purchase prices. The Draft TAR concluded that these two segments would likely continue to exist within the time frame of the rule.[261,262]

The current BEV market includes a wide variety of models either currently in production or announced for future production. Table 2.3 shows a summary of BEV models that have reached production since the 2012 FRM, and their EPA estimated range.

Table 2.3 Driving Range of MY2012-2017 BEVs

	EPA range (mi)					
BEV model	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Azure Dynamics Transit Connect	56	-	-	-	-	-
Coda	88	88	-	-	-	-
BYD e6	122	127	127	127	187	**
Toyota RAV4 EV	103	103	103	-	-	-
Mitsubishi i-MiEV	62	62	62	NL	62	59
Ford Focus Electric	76	76	76	76	76	**
Tesla Model S (85 kWh)	265	265	265	265	265	**
Nissan Leaf (24 kWh)	73	75	84	84	84	-
Tesla Model S (40 kWh)	-	139	-	-	-	-
Tesla Model S (60 kWh)	-	208	208	208	210	**
Scion iQ EV	-	38	-	-	-	-
Honda Fit EV	-	82	82	-	-	-
Smart fortwo	-	68	68	68	68	**
Fiat 500e	-	87	87	87	84	84

[BB] Penetration driven solely by the GHG standards, since vehicles attributed to the ZEV program were included as part of the EPA reference case. Absolute penetration of BEVs (counting those attributed to the ZEV program) was projected at less than 3 percent.

Kia Soul EV	-	-	-	93	93	93
BMW i3 BEV	-	-	81	81	81	81
Chevy Spark EV	-	-	82	82	82	**
Volkswagen e-golf	-	-	NA	83	83	**
Mercedes-Benz B250e	-	-	87	87	87	87
Tesla Model S (70 kWh)	-	-	-	-	234	-
Tesla Model S 70D	-	-	-	240	240	-
Tesla Model S 85D	-	-	-	270	270	-
Tesla Model S P85D				253	253	-
Tesla Model S (90 kWh)	-	-	-	265*	265*	-
Tesla Model S 90D	-	-	-	270*	294	**
Tesla Model S P90D	-	-	-	253*	270	-
Tesla Model X 90D	-	-	-	NA	257	**
Tesla Model X P90D	-	-	-	-	250	-
Tesla Model X 60D	-	-	-	-	200	-
Tesla Model X 75D	-	-	-	-	238	**
Tesla Model S 75	-	-	-	-	249	**
Tesla Model S 75D	-	-	-	-	259	**
Tesla Model S P100D	-	-	-	-	315	**
Nissan Leaf (30 kWh)	-	-	-	-	107	**
Chevy Bolt EV	-	-	-	-	-	238
BMW i3 94 Ah	-	-	-	-	-	114

Notes:
NL = vehicle not listed in Fuel Economy Guide
NA = vehicle listed but rating not available in Fuel Economy Guide
* Manufacturer applied 85 kWh EPA range figure for EPA labeling purposes
** Not yet listed in 2017 Fuel Economy Guide at time of writing

The growth in the number of BEV models has likely been encouraged in part by several factors, both regulatory and demand driven.

Among the regulatory factors, the 2017-2025 rule assigns a high GHG effectiveness to BEVs, further enhanced by assigning 0 g/mi for upstream emissions and a multiplier for the earlier years of the rule. Some manufacturers are therefore including BEVs as part of their pathway for compliance with the 2017-2025 standards. Production of BEVs also generates GHG credits that may be used for future regulatory compliance (credit carryforward) or sold to other manufacturers. Production of BEVs can also assist manufacturers in meeting fleet average criteria pollutant regulations such as EPA's Tier 2 and Tier 3 standards or CARB's LEV II and LEV III standards. And, just as with PHEVs, California's ZEV regulation continues to drive BEV production to generate ZEV credits as manufacturers prepare for ever increasing requirements through MY2025.

In addition, BEVs from all manufacturers continue to be eligible for a federal tax credit of up to $7,500, effectively reducing their net cost to consumers.[244,245] Because this credit applies to the first 200,000 eligible vehicles (BEVs and PHEVs combined) produced by a given manufacturer, it continues to influence the BEV market today. However, at current rates of production, it is possible that some manufacturers may begin approaching the 200,000 limit by 2018, with others following soon after.[246] Although reaching the limit does not immediately discontinue the incentive, which would continue to be applicable to additional sales until the second calendar quarter after it is exceeded, the amount of the credit phases out rapidly over the following year.

In addition to the federal tax credit, many states, including California and many of the states that have adopted California's ZEV regulation offer incentives for ZEVs at the state and local levels. These programs may supplement the federal program and have varying phase-out schedules and eligibility requirements.

Demand for BEVs has also been a factor in their growth. The demand for premium BEVs, such as those produced by Tesla Motors, has accounted for a significant portion of BEV sales despite their relatively high purchase price. These vehicles compete in a market segment with other high-priced vehicles and are seeing success in that segment. For example, Tesla claims that the Model S outsold all other conventional vehicles in its market segment in 2015. [263] If the performance attributes that are attracting this segment of buyers away from the conventional competitors in this space can be sufficiently retained at a lower price point, this could further drive demand for BEVs in the future. Projections for the 2017 Chevy Bolt are similarly driven by expectations of significant consumer demand.[264,265] Tesla cites over 373,000 reservations for its entry-level Model 3 as further evidence of consumer market demand for BEVs.[263] Some have even suggested that the Tesla Model 3 and the Chevy Bolt may be "breakthrough" vehicles that will open a gateway to greatly increased demand for BEVs among mainstream auto buyers.[266]

Demand for BEVs is also likely to grow in the future as consumers become more familiar with the technology. In comments on the Draft TAR, the Consumer Federation of America (CFA) cited two surveys, one reported by the Alliance of Auto Manufacturers and another performed by CFA,[267] that indicate that knowledge about BEVs is an important factor in the willingness of car buyers to consider BEVs, further stating, "the more Americans know about EVs, the more likely they are to consider this purchase." The CFA survey also found that "only a little over a quarter of respondents say they know a great deal (6 percent) or a fair amount (21 percent) about EVs," suggesting that consumer knowledge about BEVs has significant room to grow.

Another potential vector for growth in BEVs could develop from the recent boom in autonomous vehicle research by OEMs (such as GM, Ford and Tesla, among others) and tech companies such as Google. Increasingly, these efforts are being united with other mobility models such as ride sharing (for example, the partnership between GM and Lyft,[268,269] and efforts in vehicle autonomy by Uber).[270] Some have made the case that electric vehicles may be the preferred technology for autonomous applications and ride sharing models,[271] which if proven true, could act as another significant driver for BEV growth in the future.

BEVs continue to be offered at a significant price premium to conventional vehicles, largely due to the cost of the battery, as well as non-battery components that have yet to reach high production volumes. Some BEVs, particularly those targeted primarily for sale in the ZEV states, are available for purchase only in those states.

BEV production levels have grown significantly since the 2012 FRM. Through October 2016, Nissan had sold about 100,000 Leaf EVs, and GM had sold about 117,000 Volt PHEVs, Cadillac ELRs and Spark EVs combined.[272] Analysts have widely speculated that a slight decline in PEV sales in MY2015 (relative MY2014) was due at least in part to anticipation of new models with longer range and enhanced features. For example, expectations of a refreshed version of both the

2016 Volt and 2016 Leaf existed long before either became available. The 2016 Leaf offers a larger 30kWh pack, increasing range significantly, while the 2016 Volt also offers a longer range, better fuel economy and other enhancements such as improved seating.

Charging infrastructure, both at home and in public places, is a topic that is often associated with BEVs. Public charging infrastructure was explored in depth in Draft TAR Chapter 9 (Infrastructure Assessment), and is reviewed for this Proposed Determination assessment in Section B.3.2 of the Proposed Determination Appendix, where public comments received on the topic of charging infrastructure are addressed.

Since 2008, various ongoing public and private efforts to provide charging stations at workplaces, along freeway corridors, and in cities have grown the number of public stations in the U.S. to more than 16,000.[150] As mentioned in Proposed Determination Appendix B.3.2, some public comments on the Draft TAR expressed concern that infrastructure is not growing fast enough even at this pace. Mercedes-Benz commented that "infrastructure investments are not meeting expectations," while Global Automakers commented, "infrastructure is not developing as quickly as needed to support electric drive vehicles."

In addition to the consideration of these comments found in Appendix B.3.2, it is also relevant to note that since the Draft TAR was completed, two developments were announced that may increase the availability of public charging substantially. The partial settlement between Volkswagen and U.S. authorities, approved in 2016, earmarks $1.2 billion in investment over 10 years toward ZEV infrastructure, education, and access.[273] Also, in November 2016, the White House announced a network of federal, state, and local initiatives to increase accessibility to PEV infrastructure,[150] including a Department of Transportation (DOT) plan to designate 48 national "alternative fuel corridors" along major highways to provide focus for build out of charging locations by related local and state efforts.[274]

Also as discussed in Appendix B.3.2, comments from the Alliance disagreed with some of the discussion in Draft TAR Chapter 9 (Infrastructure Assessment), including the discussion of the roles and availability of home and public charging, a supposed assumption that BEV users would rely on Level 1 charging at home, and the suggestion that public infrastructure was developing as required to support the penetration levels of PEVs projected in the Draft TAR. In addition to the comments provided in B.3.2, it should be noted that Chapter 9 of the Draft TAR was provided primarily as background on charging infrastructure, and the assumptions found in that discussion are specific to the assessment presented in that discussion. Costs used in the Draft TAR and Proposed Determination analyses for home charging infrastructure were developed independently of the Chapter 9 assessment, and include significant costs for installation of home charging capability for all PEVs. Specifically, all home charging installations are assumed to incur a significant cost for installation labor, plus an additional cost for Level 1 or Level 2 charging hardware, depending on the vehicle type. These costs are outlined in more detail in Chapter 2.3.4.3.6 (Cost of Non-Battery Components for xEVs) of this TSD. Further, EPA did not assume that only Level 1 charging will be used. While PHEV20 and some PHEV40 vehicles are assigned a blend of Level 1 and Level 2 charging, all BEVs and larger PHEV are assigned 100 percent Level 2 charging. With the availability of Level 2 charging at home therefore being largely assumed and provided for in EPA's cost assumptions, the importance of public charging availability to support the projected penetration of BEVs is minimized. EPA also notes the recent charging infrastructure developments cited above, as well as recent additions of hundreds of public charging points by several OEMs (including Nissan, BMW, and Volkswagen),[275] which suggest that development of public charging infrastructure continues to proceed at a significant pace.

Trends in BEV Driving Range

Continuing growth in the BEV market has greatly expanded not only the available choice of vehicle models and trims, but also the available driving ranges. BEV driving range is largely a function of battery capacity. Figure 2.33 shows the relationship between the battery capacity of the MY2012-2017 BEVs in Table 2.3 and their EPA estimated driving range.

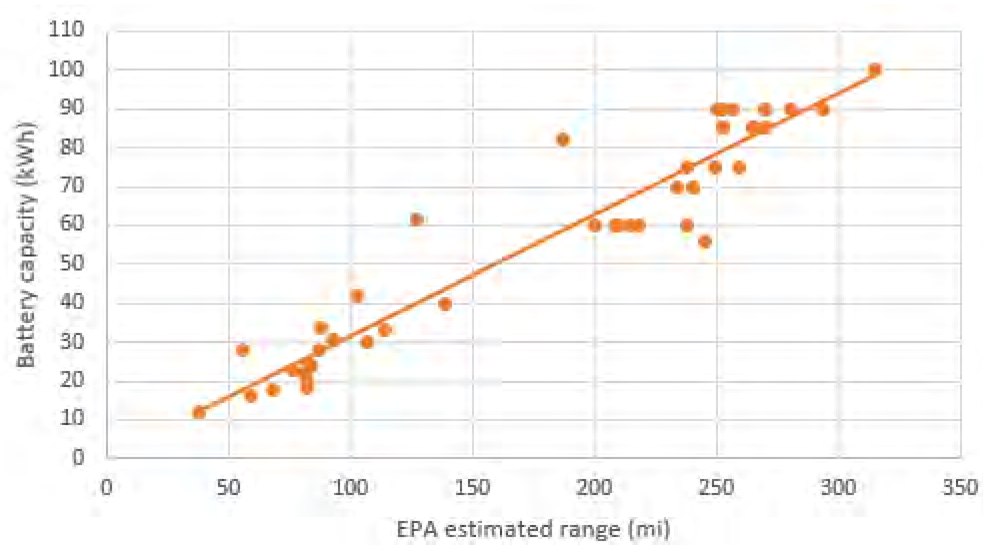


Figure 2.33 Battery Gross Capacity and EPA Estimated Range for MY2012-2017 BEVs[CC]

It has become apparent since the 2012 FRM that manufacturers have been pursuing increased driving range. Several examples serve to illustrate this trend. The Nissan Leaf was introduced in 2011 with an EPA-rated range of 73 miles. The 2013 model increased this to 75 miles, while 2014 and later models earned a higher rating of 84 miles by eliminating a partial charge option, allowing the range to be evaluated at 100 percent charge. This trend indicates that Nissan perceives increased range as a desirable goal. As another example, in January 2016, it was reported that the range of the BMW i3 might increase by about 50 percent due to improved battery chemistry and electronics;[276] by May 2016, BMW confirmed the increase in capacity, resulting in a new range of approximately 114 miles.[277] In January 2016, Volkswagen also indicated that a new version of the e-Golf could expect a possible 30 percent increase in range over the current model (or about 108 miles) due to an increase in cell capacity from 28 A-hr to 37 A-hr.[278] The 2017 Ford Focus BEV is also expected to increase its range to over 100 miles compared to its original range of 76 miles.[279] In November 2016, the 2017 Hyundai Ioniq BEV[280] was certified by EPA with a range of 124 miles.

[CC] Range figures gathered from 2012-2017 EPA Fuel Economy Guides.

Future vehicles expected to enter the consumer market soon have increasingly targeted even longer ranges. In addition to the 2017 Chevy Bolt, which recently certified for a range of 238 miles, a future version of the Nissan Leaf has been described by Nissan as targeting a 200 mile range. The Tesla Model 3 is described as offering a 215 mile range and entering production in late 2017.[281] Ford has also announced intent to introduce a 200-mile competitor, possibly called the Model E, before 2020.[282] Similar announcements have been made by Volkswagen[283] and Audi[284] among others. In November 2016 it was reported[146,147] that Toyota is planning to produce BEVs with a range of more than 300 km (186 mi) by 2020.

A trend toward increased range also seems to be playing out across manufacturers, as new products are introduced to compete in the market. For example, the Kia Soul EV was introduced in 2014 with a range of 93 miles, surpassing the Leaf. Not long after in 2015, Nissan announced the 2016 Nissan Leaf, offering an EPA range of 107 miles with a new 30 kWh battery pack. In late 2016, General Motors announced that the 2017 Chevy Bolt was certified for a range of 238 miles, significantly greater than the rumored 215 mile range of the upcoming Tesla Model 3 with which it will directly compete.

Even Tesla Motors, which already offers a range in excess of 200 miles in all of its current vehicles, has shown an interest in increased range as evidenced by regular increases in battery capacity. After announcing in 2012 that the Tesla Model S would be available in three battery sizes (40 kWh, 60 kWh, and 85 kWh), the 40 kWh version was canceled in 2013, prior to its production. In April 2015, the battery capacity of the 60 kWh version was increased to 70 kWh, which along with powertrain improvements increased its range from 208 miles to 240 miles. In September of the same year the 85 kWh version was increased in capacity to 90 kWh by use of an improved chemistry.[DD] This was followed by another increase to 100 kWh, which increased the EPA estimated range to 315 miles.[285] According to an informal statement attributed to Tesla CEO Elon Musk, 100 kWh may be the maximum capacity that will be offered for the Model S.[286] Tesla also announced in 2015 an available battery upgrade for the discontinued Roadster that would increase its range by about 40 percent.[287]

Manufacturers have frequently cited customer demand in the quest for increased range. When the 40 kWh Model S was canceled, Tesla attributed the decision to low demand, further saying, "Customers are voting with their wallet that they want a car that gives them the freedom to travel long distances when needed."[288] Although this statement clearly promotes Tesla's market strategy of offering a longer driving range than other BEV-manufacturing OEMs, similar sentiment has been expressed by other OEMs in marketing their electrified vehicles or announcing future plans. Customer demand for an affordable BEV with a longer driving range than currently available is implicit in the 200-mile range target of both the future Nissan Leaf and the 2017 Chevy Bolt.

As a way of increasing range, simply increasing the battery capacity in the absence of other improvements may be prohibitive because it increases the cost of the battery accordingly. On the other hand, improved battery manufacturing or battery chemistry (in terms of cost or energy density) might enable a larger capacity while offsetting some of the cost penalty of a larger battery. For example, both Tesla and Nissan have utilized improved chemistry to increase

[DD] The manufacturer chose to apply the 85 kWh EPA range figure to the 90 kWh version for EPA labeling purposes. Marketing materials attribute an additional 6% range to the 90 kWh version.

capacity within the existing footprint of their respective packs; while GM and Nissan have hinted strongly at improved chemistry being the enabler of the affordable 200-mile range target for the Bolt and future Leaf. These and other examples are discussed in more detail in Chapter 2.2.4.5.1 (Battery Chemistry).

Increasing the usable capacity (i.e. widening the usable state-of-charge window) of the battery may be another route for increasing range; for example, by use of an improved chemistry, or by acting on experience that indicates that the existing buffer capacity may be reduced. Improvements in battery management systems (BMS) may also lead to greater utilization of the available battery capacity. Examples of OEM activity in this area are reviewed in more detail in Chapter 2.2.4.5.3 (Usable Energy Capacity).

Range can also be increased by reducing vehicle energy consumption. This can be done by improving the energy efficiency or weight of non-battery powertrain components (electric machines and power electronics) or even the battery itself. For example, the dual motor versions of the Tesla Model S achieve a slightly higher range than the single motor versions due to an improved powertrain efficiency resulting from the ability to selectively operate one or both motors as conditions warrant. Range may also benefit from standard road load improvements such as light-weighting, improved aerodynamics, and lower rolling resistance.

In addition to increased range, a larger battery may carry other ancillary benefits for manufacturers and consumers. Because a large battery stores more energy per charge cycle than a small battery, it is likely to experience fewer charge-discharge cycles in the course of providing a given number of vehicle miles. For example, a battery that provides for a range of 200 miles can provide a lifetime mileage of 150,000 miles with about 750 charge-discharge cycles, while a 100-mile battery may require 1,500 cycles. The smaller number of expected cycles may promote a longer battery lifetime or relax manufacturer provisions for battery durability, such as increasing the permissible charge rate or the usable capacity. A larger battery might also experience a much shallower average state-of-charge (SOC) swing in the course of meeting its mileage target, with similar implications for durability. Another advantage of a large battery is a reduction in average discharge rate (C-rate), which can allow consideration of chemistries and configurations that would not be suited to smaller batteries. For example, Tesla may have selected a chemistry that supports notably low C-rates in recognition that the large size of the battery acts to minimize per-cell power requirements.[289] Of course, a drawback of a larger battery over a smaller battery is its greater weight, which tends to reduce the overall energy efficiency of the vehicle.

In the same way that cabin air conditioning can have a significant impact on fuel economy of conventional vehicles,[290] both heating and air conditioning can have a strong impact on BEV energy efficiency and range. While the impact of passenger comfort on range can be great for both BEVs and PHEVs, BEVs are at a particular disadvantage because all energy for heating and cooling must come from the battery. In contrast, PHEVs may choose to operate the engine if needed (for example, the Chevy Volt operates the engine to help with cabin heating in cold weather). Cabin heating and cooling for BEVs is therefore an active area of research toward increasing BEV range.[291, 292]

Some BEVs, such as the Nissan Leaf, have employed heat pump-based HVAC in place of resistive heating. When the temperature differential between the outside air and the desired cabin temperature is not too large, this method can be much more efficient than resistive heating at controlling cabin temperature. Another approach to passenger comfort that has been used for BEVs and PHEVs involves heated and cooled surfaces, for example, the steering wheel and seats, instead of or in addition to heating the cabin air, which one study has shown can reduce cooling and heating energy in a PHEV by about 35 percent.[293] Pre-conditioning the passenger cabin while plugged in to a charging station is yet another approach, which can reduce the use of onboard energy for heating and cooling (although it does consume energy at the station).

Modeled BEV Ranges in the Draft TAR and this Proposed Determination

As noted in the Draft TAR, the EPA analysis models three BEV range configurations (BEV75, BEV100 and BEV200). As previously noted, the Draft TAR adopted BEV200 in place of BEV150 due to several market developments since the 2012 FRM. Tesla vehicles with a range well in excess of 200 miles are growing in production rates and market share as well as range. Although these vehicles currently constitute a premium segment that may not be fully representative of a mass-market vehicle, their success at achieving significant market penetration shows that at least one OEM has found it preferable to comply with the 2017-2025MY standards and generate additional GHG credits by producing long-range BEVs. Announcements from Nissan, GM, and several other OEMs target a 200-mile BEV range, suggesting that BEV200 may become prevalent in the future BEV market.

In the public comments to the Draft TAR, Volkswagen voiced a concern that over the longer term, BEV200 may not provide a long enough driving range to compete with conventional vehicles, and suggested that EPA consider adding an even longer range vehicle, which would have an accordingly higher cost than BEV200 due to having a larger battery.

EPA acknowledges that BEV200 represents a shorter range than seen in many current premium segment vehicles with well over 200 miles range, and that over time the consumer market may increasingly exceed BEV200 in order to compete with conventional vehicles. But despite the announcement of the Chevy Bolt at 238 miles range, announcements of other near-term future BEVs continue to target a range closer to BEV200. For example, Ford has announced intent to introduce a BEV, described as having an approximately 200-mile range, before 2020.[294] It has also been reported[146,147] that Toyota is planning to produce BEVs with a range of "more than 300 km" (or 186 mi) by 2020. Similarly, it continues to appear that Nissan is likely to be targeting a 200-mile real-world range with a future version of the Leaf.[295] Tesla has suggested that the Model 3 will be available with at least 215 miles of range, which also is not far from BEV200. Of course, although Tesla may choose to increase the Model 3's range to compete with the Bolt, this is still uncertain. It remains unclear whether the market will coalesce around longer range vehicles at a somewhat higher cost, or settle at a lower range with a lower cost. Further, to the extent that manufacturers pursue future range increases by taking advantage of ongoing reductions in battery cost per kWh, the total cost of the battery could remain relatively constant even as range gradually exceeds BEV200.

Compared to BEV75 or BEV100, there may be limited potential for BEV200 to be selected by OMEGA as part of a cost-effective compliance path, because the relatively high cost of the larger battery is likely to overshadow any gain in effectiveness. That is, since BEV75, BEV100, and BEV200 are all assigned a GHG effectiveness of 100 percent (when upstream emissions are assessed at 0 grams per mile), the incremental cost of BEV200 vs. BEV75 or BEV100 strongly discourages its selection on a pure cost-effectiveness basis. Although this effect is reduced in this Proposed Determination analysis because the compliance model now phases-in an accounting for upstream emissions for PEVs between 2021 and 2025, it still has some influence. Due to the structure of the OMEGA model and the low potential for even BEV200 to be selected on a pure cost-effectiveness basis, EPA is currently choosing to remain with BEV200 as a modeling construct. (See also the discussion of public comments relating to BEVs in Chapter 2.3.4.3.5).

As discussed in Draft TAR Chapter 5.3, EPA updated assumptions for many of the xEV parameters that affect battery sizing for the Draft TAR analysis. In Chapter 2.3 of this TSD, EPA further updates certain assumptions for the Proposed Determination analysis, as suggested by updated information and public comment on the Draft TAR. These include assumptions for usable capacity, electric powertrain efficiencies, and power ratings of electric machines and power electronics. EPA is also updating the assumptions for road loads as they affect battery sizing for BEVs. For further details on these changes, see Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

Trends in BEV Motor Sizing

In addition to driving range, the motor power of BEVs is another important input to EPA's projection of battery and system costs for BEVs. As discussed previously with respect to PHEVs, the 2012 FRM analysis had assigned BEVs of a given vehicle class a motor power rating that would preserve the same engine-power-to-weight ratio observed in conventional vehicles of that class. The Draft TAR found that this method overestimated the rated peak motor power necessary to achieve a given acceleration performance. The Draft TAR developed an improved methodology that more accurately assigned motor power specifications.

As previously discussed in relation to PHEVs, accurately assigning the motor power of a BEV is important for several reasons. First, the motor power rating has a direct effect on the battery power rating, which determines its power-to-energy (P/E) ratio and its cost. Second, EPA accounts for the weight of the electric motor and power electronics as a function of power. Finally, an accounting of motor cost requires an accounting of motor power. As in both the 2012 FRM and Draft TAR analyses, for this Proposed Determination analysis EPA estimates electric motor and power electronics costs as a function of peak output power, in accordance with several examples of similar industry practice.[EE]

As with PHEVs (discussed in the previous section), the Draft TAR found that the FRM analysis tended to assign significantly higher BEV motor power ratings than the majority of BEV manufacturers subsequently found necessary to provide in their MY2012-2016 vehicles. Accordingly, in the Draft TAR, EPA revised the BEV motor power ratings to be closer to those suggested by the power-to-weight ratios that BEV manufacturers appear to be following, while maintaining an estimated acceleration performance equivalent to conventional vehicles.

Assigning a more accurate power rating provided greater fidelity in the projected cost of both the battery and non-battery components of BEVs. More detail on the way BEV battery and non-battery components were sized in the Draft TAR and revised for this Proposed Determination analysis are discussed in Chapters 2.2.4.4.6 (Relating Power to Acceleration Performance) and 2.3.4.3.7 (Cost of Batteries for xEVs).

[EE] For more discussion of the decision to scale motor cost to power output, see Draft TAR Section 5.3.4.3.6, Cost of Non-Battery Components for xEVs.

Trends in BEV Battery Sizing

To assess the fidelity of the EPA battery sizing methodology, the Draft TAR compared the 2012 FRM projections of BEV battery capacity and range to the BEVs that entered the market during MYs 2012-2016, and generally found that the 2012 FRM analysis had predicted significantly larger battery capacities for a given range. The Draft TAR analysis revised these figures accordingly by making changes to many of the parameters that determine BEV battery sizing, as described in the Draft TAR.

Figure 2.34 compares the battery capacities of MY2012-2016 BEVs to the battery capacities that were estimated for the Draft TAR analysis.

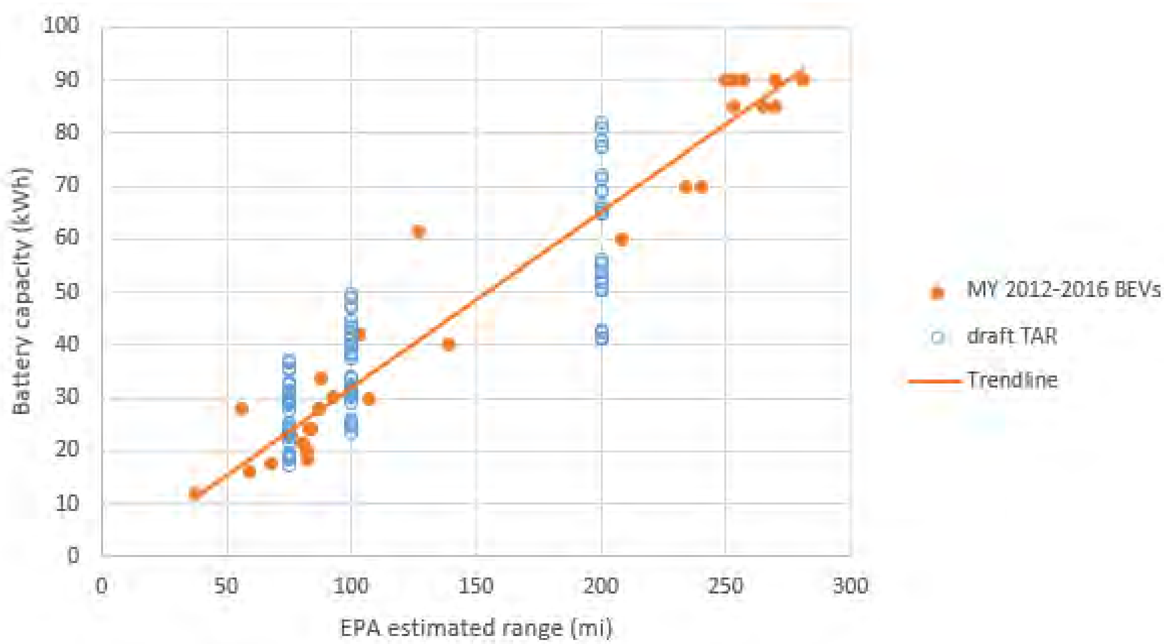


Figure 2.34 Comparison of 2012-2016MY BEV Battery Gross Capacities to Draft TAR Estimates

For each BEV range modeled (75, 100, and 200 miles), the Figure shows the battery capacity estimates used in the Draft TAR. For each BEV range, several values are seen, corresponding to each of the vehicle classes (Small Car, Standard Car, Large Car, etc.) and glider weight reductions of 0 percent to 20 percent.

It can be seen from the plot that the Draft TAR estimates centered quite well upon the trendline established by the population of production vehicles of a similar range. This represented a significant improvement over the 2012 FRM projections, which had significantly overestimated capacities. As discussed in the Draft TAR, the improvement was the result of updating many of the parameters that are influential to the estimation of battery capacity, as described in Chapter 5.3 of the Draft TAR. This Proposed Determination analysis makes additional adjustments to the PHEV battery sizing methodology, based on updated information and public comments on the Draft TAR, which are discussed in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

2.2.4.4.6 Relating Power to Acceleration Performance

As discussed previously in the sections on PHEVs and BEVs, the high low-end torque associated with electrified powertrains means that the relationship between rated powertrain power and acceleration performance may differ substantially for electrified vehicles compared to conventional vehicles. Understanding the relationship between the rated power of an electrified powertrain and the performance it provides is important to properly sizing the powertrain for a target performance level. This section examines this issue further by comparing the power ratings and performance of electrified vehicles currently on the market to that of conventional vehicles, and deriving an empirical relationship between power and 0-60 time that better applies to electric drive. Although a more detailed discussion was presented in the Draft TAR, this Proposed Determination analysis adds additional acceleration data for MY2017 PEVs, which also serves to update the empirical relationship from that presented in the Draft TAR.

One of the most common metrics of acceleration performance is the time it takes a vehicle to accelerate from zero to sixty miles per hour, also known as the 0-to-60 time. Although there are other metrics that describe acceleration performance, including metrics such as 0-to-30 time, 30-to-60 time, and quarter-mile time (and gradeability metrics as well), 0-to-60 time is likely the most familiar metric for understanding the acceleration performance of a vehicle.

While in widespread popular use, the 0-60 metric is not reported by manufacturers to EPA nor is its measurement subject to uniform standards. As an alternative, acceleration times of vehicles with conventional powertrains are sometimes estimated by means of an equation developed by Malliaris et al.[296] The Malliaris equation relates 0-to-60 time to the power-to-ETW ratio of a vehicle. This power-law equation has two numerical coefficients empirically obtained from a least-squares fit of vehicle performance data. Until a different method was adopted in 2014, EPA historically used this equation and coefficients to estimate acceleration performance of vehicles for pre-2014 editions of the annual Trends Report.[297,FF]

The Malliaris equation is depicted in Equation 1 below, with the coefficients 0.892 and 0.805 representing conventional vehicles with automatic transmissions.

$$t = 0.892\left(\frac{hp}{lb\ ETW}\right)^{-0.805}$$

Equation 1. Malliaris equation for 0-60 acceleration time in seconds

The Malliaris equation suggests that the acceleration performance of a vehicle may be modeled as a function of power-to-ETW ratio, and therefore it suggests that acceleration levels may be maintained by maintaining a similar power-to-ETW ratio among modeled vehicles. It also suggests that a specific 0-60 time can be targeted by specifying the corresponding power-to-

[FF] Subsequent editions of the Trends Report have used a newer method developed by MacKenzie et al.[FF] that EPA believes to be more accurate, particularly for newer vehicles. However, the MacKenzie method is not directly applicable to electric powertrains due to the requirement for ICE-specific inputs.

ETW ratio. For example, Figure 2.35 plots the Malliaris equation (converted to SI units) for a range of power-to-ETW ratios, showing the approximate 0-60 times that it would predict.

The fact that the Malliaris equation is derived from an analysis of conventional powertrains suggests that it might not be equally valid for electrified powertrains. The Draft TAR recognized that a significant number of PEV models had entered the market since the 2012 FRM, and took this opportunity to characterize the acceleration performance of a selection of MY2012-2016 PEVs for which curb weights and estimated all-electric 0-60 times were available.

To illustrate, Figure 2.35 plots the approximate 0-60 mph acceleration times of MY2012-2017 BEVs and PHEVs as a function of their power-to-ETW ratio, as expressed by rated peak motor power (kW) divided by test weight (the published curb weight in kg, plus 136 kg payload).[GG] Acceleration times were collected from publicly available sources including manufacturers and press organizations, and in some cases were averaged when estimates from different sources had slight variation. PHEVs for which an all-electric (battery only) acceleration time could not be established were not included.

An empirical trendline was derived from this data and is shown in the Figure as a thin orange line. For comparison, the acceleration times that would be predicted by the Malliaris equation for the same range of power-to-ETW ratios is shown in the Figure as a heavy black line. As shown by Equation 2, the empirical trendline has the same equation form as the Malliaris equation, but with different coefficients of 1.1321 and -0.733 that result from a least-squares fit to the PEV data as expressed in SI units for power and weight.[HH]

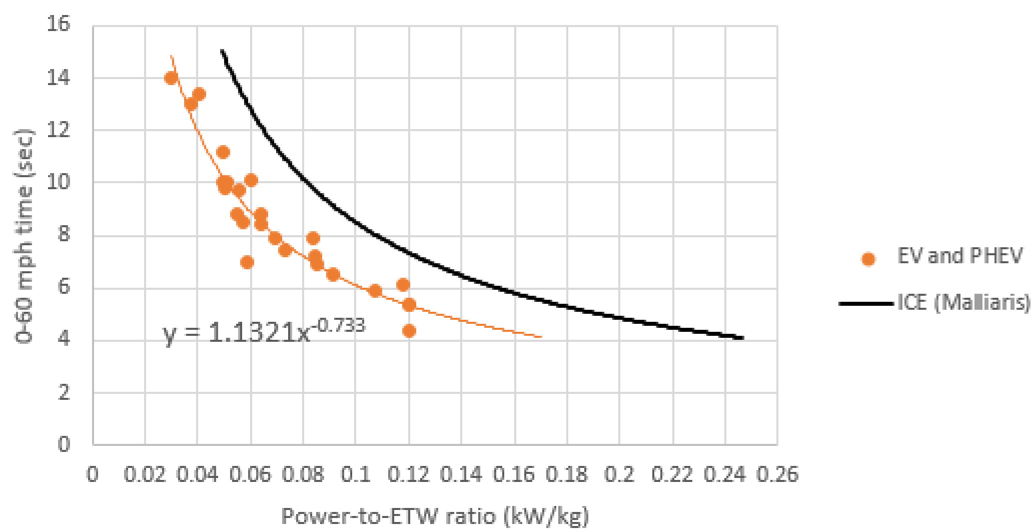


Figure 2.35 Acceleration Performance of MY2012-2017 PEVs Compared To Targets Generated By Malliaris Equation

[GG] Tesla high-performance vehicles represented by 85 kWh Model S.

[HH] The coefficients are different from those reported in the Draft TAR due to the addition of several MY2017 BEVs to the data set.

$$t = 1.1321\left(\frac{kW}{kg\ ETW}\right)^{-0.733}$$

Equation 2. Empirical equation for 0-60 all-electric acceleration time of MY2012-2017 PEVs

As described in the Draft TAR, it can be seen that the 0-60 times for MY2012-2017 electrified vehicles fall on a significantly different line than that described by the Malliaris equation. As the Draft TAR found, using the Malliaris equation to size electrified powertrains results in significantly faster projected 0-60 acceleration times than would likely be intended. For example, to target a 0 to 60 mph acceleration time of 10 seconds, the Malliaris equation (shown by the heavy line) would indicate that the motor should be sized to achieve a power-to-ETW ratio of 0.08 kW/kg. However, the empirical PEV trendline indicates that this power-to-ETW ratio would actually provide an electric powertrain with an acceleration time of about 7 seconds.

As described in the Draft TAR and depicted in Table 2.4, the 2012 FRM therefore had effectively assigned significantly greater acceleration times than intended, which also inflated the necessary motor and battery power ratings.

Table 2.4 PEV Acceleration Performance Intended in the FRM and Projected Probable Performance

	0-60 mph time (sec)	
Class	**FRM intent**	**FRM actual**
Small Car	11.1	7.7
Standard Car	9.5	6.6
Large Car	6.8	4.7
Small MPV	11.3	7.9
Large MPV	9.5	6.6
Truck	8.8	6.1

The empirically derived relationship shown in Equation 2 is used for PEV motor power assignment in this Proposed Determination analysis. The equation differs slightly from that used in the Draft TAR analysis due to the addition of several MY2017 vehicles to the data set.[II] This change has negligible effect on the resulting motor power assignments.

2.2.4.5 Developments in Electrified Vehicle Battery Technology

For many types of electrified vehicles, particularly PHEVs and BEVs, battery cost is the largest single component of vehicle cost. Battery pack cost is determined in part by the configuration of the pack, which should be tailored to the specific performance goals of the vehicle.

Pack configuration may be decomposed into a large number of primary design parameters which the vehicle designer can specify to determine the performance of the pack and ultimately its cost. In configuring a pack, the primary performance targets are energy capacity in kilowatt-hours (kWh) and power capability in kilowatts (kW). These performance targets are determined by design choices such as: battery chemistry (although all PEVs currently use lithium-ion chemistry, this is a family of chemistries composed of a number of specific cathode and anode

[II] For the equation used in the Draft TAR, see Draft TAR p. 5-329.

formulations); pack voltage, usable portion of total capacity, cell capacity (Ampere-hours per individual cell), cell topology (the electrical and physical arrangement of cells and modules in the pack), and cooling method (passive or active, and air or liquid), among others. Further, for a pack defined by a given set of these design parameters, the assumed annual manufacturing volume will also influence the projected cost.

It is customary to refer to battery cost in terms of cost per kWh. However, in order to make valid comparisons on this basis it is important to understand that cost per kWh is strongly influenced by the power-to-energy (P/E) ratio of the battery. Intuitively, a BEV battery optimized for energy storage capacity (low P/E) will have a low cost per kWh because the materials and construction are oriented toward providing maximum energy capacity. Conversely, an HEV battery optimized for power (high P/E) will have a higher cost per kWh, because the materials and construction are oriented toward providing power, while the metric of cost per kWh continues to focus on energy. For these reasons, cost per kWh figures derived from energy-optimized BEV or PHEV battery packs should not be used to estimate the cost of a power-optimized HEV pack, or vice versa. Comparisons of cost per kWh are only valid when the applications have a similar P/E ratio.

It is also important to be aware of whether a cited cost per kWh is on a cell basis or a pack basis. Figures found in press or manufacturer literature may be of either type. Costs cited on a cell basis will be much lower than for a full pack that includes battery management, disconnects, and thermal management. As in the 2012 FRM and Draft TAR analyses, for this Proposed Determination analysis all cost per kWh figures are presented on a pack basis.

Finally, the energy capacity of a battery pack (kWh) may be characterized either by gross capacity or usable (net) capacity. Gross capacity, also known as nominal or nameplate capacity, is the total amount of energy that can be reversibly stored in a complete charge and discharge cycle of the battery, without regard to long term durability. It is a relatively fixed quantity that is a function of the amount of electrode active materials contained in the battery. Usable capacity is the portion of gross capacity that the manufacturer believes can be regularly used in an application while maintaining a desired level of durability. Although usable capacity is the metric that relates best to performance attributes such as driving range, usable capacity varies widely among different vehicle types and individual models of each type. For consistency it has become customary to refer to the size of xEV battery packs by their gross capacity, and to refer to battery cost per gross kWh. As in the 2012 FRM and Draft TAR analyses, the Proposed Determination analysis follows this standard.

2.2.4.5.1 Battery Chemistry

EPA bases its battery cost analyses on outputs of the ANL modeling tool BatPaC[135], which models several well established lithium-ion chemistries. As shown in Table 2.5, the choice of chemistries available in BatPaC includes:

Table 2.5 Lithium-ion Battery Chemistries Available in ANL BatPaC

Chemistry	Cathode	Anode
LMO-G	Lithium-Manganese Oxide	Graphite
LMO-LTO	Lithium-Manganese Oxide	Lithium Titanate Oxide
NMC333-G	Nickel-Manganese-Cobalt (3-3-3)	Graphite
NMC622-G	Nickel-Manganese Cobalt (6-2-2)	Graphite

NCA-G	Nickel Cobalt Aluminate	Graphite
LFP-G	Lithium-Iron Phosphate (Olivine)	Graphite

Certain chemistries are better suited for certain applications than for others. For example, the specific versions of NMC chemistry that are modeled by BatPaC are well suited for packs having a large energy capacity such as BEV packs, but due to limits on area specific impedance (ASI), they are not as well suited for small, power-dense packs for HEVs. Considerations such as these ultimately led to the chemistry choices EPA employed for the FRM and Draft TAR analyses. In the Draft TAR, BEV and PHEV40 batteries were configured with NMC441-G, while PHEV20 and HEV packs were configured with LMO-G. For the Draft TAR analysis this was updated to NMC622-G and a blended formulation of 75 percent LMO and 25 percent NMC, respectively. These chemistries continue to be representative of industry practice and so were retained for the Proposed Determination analysis.

Since the 2012 FRM, the lithium-ion family of chemistries has continued to dominate xEV battery technologies seen in current and announced production vehicles. As expected, NMC/NCM cathode formulations are increasingly being seen in BEVs announced since the FRM, including in mixed formulations with LMO. For example, the Kia Soul BEV uses an NCM cathode.[298] In the 2015 NAS report (p. 4-26), the committee mentions the use of NMC cathodes for the 2020 to 2025 time frame, lending further support to EPA's choice. PHEVs and HEVs are being seen not only with LMO-dominant cathode formulations, such as in the original Chevy Volt, but also with NMC and blended NMC cathode formulations, as in the 2016 Chevy Volt,[299] the Ford C-Max Hybrid HEV and C-Max Energi PHEV.[300] These are presumably optimized for the relatively high P/E ratio of these applications. Lithium-iron phosphate cathodes are also being promoted for HEV use.[301] While it is not possible for BatPaC to model every (often proprietary) variation in cathode formulation, the available choices are likely sufficient to represent the cost spectrum applicable to this family of chemistries.

As discussed in the Draft TAR, use of pure LMO cathodes in xEV batteries has gradually trended toward blends of NMC and LMO. [302] In particular, most HEV batteries currently in production appear to utilize either NMC or LMO blended with NMC. For example, the 2016 Chevy Malibu Hybrid battery is said to use an NMC cathode[303] while the Volt uses NMC blended with LMO.[299]

Version 3 of BatPaC, released for beta in November 2015, added the more common NMC622 cathode formulation in place of NMC441, and a user-selectable blend of NMC and LMO. The Draft TAR analysis was thus able to adopt a blended NMC-LMO cathode for HEV and PHEV20 batteries, to better represent their usage in existing platforms. The November 2015 Version 3 continues to be the most current version and was retained for use in the Proposed Determination analysis.

At the time of the 2012 FRM, practically every production xEV was using a Li-ion chemistry, with the nickel-metal-hydride (NiMH) battery of Toyota HEV products being the primary exception. After using NiMH in the Prius since its introduction in 1997, there are signs that even the Prius may be moving toward Li-ion. By 2012, Toyota had already adopted a lithium-ion chemistry for the Prius PHEV, a platform which requires a larger battery capacity than the standard hybrid. In October 2015, Toyota announced that the 2016 Prius hybrid would also begin offering a Li-ion battery as an option.[166,304] In November 2016, it was reported that Toyota has taken further steps to incorporate lithium-ion technology in its portfolio by announcing plans to use Li-ion for the Prius Prime and potentially for future BEVs.[305]

Since the 2012 FRM, industry research has continued into more energy- and power-dense variations of the lithium-ion platform, including improved cathode material blends, lithium-rich, manganese-rich, nickel-rich, and higher voltage (e.g. 5V) spinel cathodes, and the use of silicon in the anode. Other research is concerned with even more advanced platforms, including lithium-sulfur, and several metal-air chemistries (lithium-air, aluminum-air and zinc-air) among others. These advanced chemistries are not yet available in cells suitable for xEV use, but potential examples are beginning to emerge.

Lithium-sulfur (Li-S) cells are beginning to be seen in some highly specialized applications. A Li-S cell manufactured by Sion Power is used in the Airbus-sponsored Zephyr high-altitude unmanned aerial vehicle (UAV) to store solar energy for nighttime flight. The low-temperature performance of Li-S cells may have in part led to the choice of this chemistry for this application.[306] Oxis Energy is expected to release a commercial Li-S battery cell in 2016, with an eye toward xEV applications.[307,308]

Silicon is also beginning to appear in the anode of commercial Li-ion cells. While it takes 6 carbon atoms in a carbon anode to accept 1 lithium ion, a silicon atom can accept several. However, uptake of lithium ions by silicon is accompanied by extreme volumetric expansion, leading to complications such as disintegration of the anode matrix and loss of electrical conductivity. For this reason, many are currently focusing on very small additions of silicon to an otherwise carbon-based anode to achieve incremental improvements in specific energy. In 2015 Tesla Motors Inc. announced a 90-kWh Model S pack that was said to achieve a greater specific energy by including a small amount of silicon in the anode.[309]

Solid-state lithium-ion cell technology is another active area of research. Most solid-state construction concepts retain the traditional anode and cathode couples but replace the liquid electrolyte with a solid (usually polymer) electrolyte. Others seek to enable use of lithium metal as the anode by leveraging the solid nature of the electrolyte to prevent dendrite formation. Solid state construction leads to the possibility of more efficient production techniques, such as building complete battery cells by printing or deposition, potentially in complex shapes that conform to available packaging space, or in flat shapes that could be integrated structurally with the vehicle. Minimizing the resistance of the solid electrolyte is a primary research target for enabling this technology. As an indicator of interest in this technology, the British appliance manufacturer Dyson purchased the solid-state lithium-ion battery firm Sakti3 for $90 million in October 2015.[310] In March 2016, it was widely reported that Dyson may be planning to produce an electric vehicle, as suggested by evidence that the company is receiving U.K. government funding for this purpose.[311] Similarly, Bosch, a major automotive supplier, acquired solid-state lithium-ion developer Seeo in 2015, citing potential applicability of the technology for increasing the range of electric vehicles.[312]

While promising, these and similar early examples of Li-S electrode couples, silicon anodes, and solid-state construction will need time to show that engineering targets for cycle life, dimensional stability, and durability in demanding xEV applications have been reliably met. Until then, reliable estimates of their cost or commercial availability will not be available. Metal-air chemistries will require even more development before they will be mature enough to characterize their potential use in automotive applications or their production costs. The 2015

NAS report (Finding 4.5, p. 4-44) further supports the conclusion that "beyond Li-ion" chemistries such as these are unlikely to be commercially available during the time frame of the rule. At this time EPA considers it unlikely that fully proven forms of such chemistries will become commercially employed in xEV applications on a broad scale during the time frame of the MY2022-2025 standards. The developmental state of these chemistries and the unavailability of well-developed cost models prevent their inclusion in our analysis.

2.2.4.5.2 Pack Topology, Cell Capacity and Cells per Module

Pack topology refers in general to the way cells and modules are electrically connected to form a pack. Modules are collections of cells that act as building blocks for a pack. Cell capacity is the charge capacity of an individual cell, and is closely related to pack topology.

To fully understand developments in these areas and EPA's choices for these parameters in the modeling of battery packs for costing purposes, an example of how these parameters interact will now be presented as background.

One approach to configuring a battery pack would start with a target pack voltage for the application. Target voltage typically refers to the nominal voltage expected at about 50 percent SOC. For PEVs, the targeted voltage is typically between 300 V and 400 V. The most commonly used Li-ion chemistries provide a nominal voltage between 3 V and 4 V per cell. Assuming a 3.8 V cell and a target of 365 V, a BEV pack might be constructed of 96 cells connected as series elements (3.8 V * 96 = 365 V). The target energy capacity of the pack (kWh) would then be achieved by specifying the capacity of each cell. The larger the target pack capacity, the larger the required capacity of the cell. In this example, to target a 24 kWh pack capacity, each series element would need to have a capacity of about 66 A-hr:

24,000 W-hr / 3.8 V / 96 cells = 66 A-hr

Manufacturers have several options for providing this cell capacity. The simplest would be to manufacture cells of 66 A-hr capacity. This results in one cell at each series position, minimizing the number of cells and interconnections, potentially minimizing the cost of the pack. In practice, manufacturers may instead be compelled to use smaller cells, perhaps to better address thermal management considerations, or to match an existing cell size offered by a cell supplier. The 66 A-hr required at each series position might then be provided by two 33 A-hr cells, or three 22 A-hr cells, connected in parallel. The exact cell capacity could vary slightly to match available products if some variation in pack capacity or voltage are permissible. Increasing the pack capacity, for instance doubling it to 48 kWh, could in theory be achieved either by doubling the number of series elements (from 96 to 192) or by doubling the A-hr capacity of each series element (to 132 A-hr). The first option is problematic because it would double the voltage to 730 V, which presents a potential safety issue and may be outside the typical operating voltage range of available power electronics. The larger cell capacity of the second option may be difficult to achieve in a single cell while maintaining effective thermal and current distribution characteristics within the cell. For these reasons, larger packs are often found to include parallel strings of two or more smaller cells at each series position. Tesla products are an extreme example, composed of thousands of very small cells, which results in as many as 36 cells in each series position.

Another important aspect of pack topology is the format of the individual cell. Most industry cell development and current automotive cell applications continue to be centered on prismatic (rectangular) cell formats composed of stacked or flat-wound electrode strips housed in metal cans or polymer pouches. ANL BatPaC models a prismatic format housed in a stiff polymer pouch. Tesla is almost unique among PEV manufacturers in its use of small, cylindrical 18650-format cells.[313] But because Tesla continues to build significant market share, this difference has potential significance to the projection of future pack costs. Also, there is some evidence that other manufacturers are beginning to consider cylindrical cells. In 2015 Volkswagen announced the R8 e-tron which has a pack composed of cylindrical cells; potentially, other products such as the Q6 e-tron and the Porsche Mission E might also share this format if this is an indication of VW's future battery construction approach. Additionally, in November 2015 Samsung SDI announced that it would supply cylindrical cells to a China customer for use in electric SUV battery packs.[314] According to one analysis, about 38 percent of currently available BEV models have packs composed of cylindrical cells, with the rest roughly evenly divided between prismatic pouch and prismatic metal can[315] (although it is unclear whether the relatively large number of Tesla sub-models are counted as separate models). About 40 percent of HEV models use packs composed of cylindrical cells, according to the same source.

Despite the differences between prismatic and cylindrical cell formats, there may be limited potential for large differences in pack costs to result. First, material costs per unit energy storage are likely to be similar on a cell basis. Cylindrical cells and prismatic cells differ primarily in the manner in which layers of active materials are packaged together, one being a spiral winding of a single electrode strip and the other a stack of multiple smaller strips. Although the assembly process is different, both methods utilize active material with similar efficiency. This is significant because material costs are the most dominant component of total cell cost.[135,316,317,153] Second, while cylindrical cells may benefit from a somewhat simpler cell manufacturing process and the highly commoditized status of the 18650 format, the large number of 18650-format cells that must be connected to build a pack may work against these advantages. While larger cylindrical cells might be used, their heat dissipation properties may limit their practical size. While 18650-format cells have good thermal qualities, larger cells begin to face challenges in rejecting heat from the core of the cylinder where the maximum temperature tends to develop.[318] Despite Tesla's success with the cylindrical format, it remains unclear whether either format possesses a greater potential to eventually minimize pack cost. EPA therefore expects that the cost estimates of the BatPaC model should be reasonably accurate for both cell formats.

xEV packs are often configured with a single series string of cells. Larger BEV packs may be configured with a parallel string of two cells in each series position, in order to limit voltage to the desired range and limit the required A-hr capacity of the cells. xEV battery packs found in production vehicles (with the exception of Tesla, as previously mentioned) are largely continuing to follow the practice of having one, two or three cells in parallel at each series position.

EPA expects that as the industry continues to mature, manufacturers will continue to pursue economies by gradually optimizing cell capacities to the requirements of the application, including an increase in cell capacity for large packs in order to minimize the number of cells while limiting the total voltage. As described in the Draft TAR, there is evidence that manufacturers are continuing to increase BEV cell capacities.

As announced by GM in October 2014, the Chevy Volt generation 2 battery pack has fewer cells than the original generation (192 vs 288) that are each about 50 percent greater in capacity. In the original pack, each series element was composed of three cells in parallel, while the new configuration has only two.[319] The 30 kWh trim of the 2016 Nissan Leaf, announced in September 2015, achieves its increased capacity within about the same size and footprint of the lower-trim 24 kWh pack by utilizing a more energy dense chemistry variation. The number of cells remained unchanged at 192, implying an increase in the A-hr capacity of each cell.[320] Similarly, the 2017 BMW i3 achieves a 50 percent increase in capacity over the earlier model, within the same pack volume, by using a 94 A-hr cell in place of a 60 A-hr cell.[277]

The latter example further suggests that cell suppliers are pushing the envelope of cell capacity for vehicular applications beyond the limit used in the 2012 FRM analysis, which was set at 80 A-hr for BEV cells. The 60 A-hr cell format that Samsung SDI had been supplying to BMW for the pre-MY2017 BMW i3 pack was already one of the larger light-duty BEV cell formats in use when it was replaced by the 94 A-hr format. At AABC 2015, Samsung SDI presented further plans for manufacturing prismatic cells of 90 to 120 A-hr by 2020.[321] The presenter also mentioned a goal of eventually producing 180 A-hr cells for BEV use, using a new chemistry with high NCM content plus silicon. This suggests that at least some suppliers are already anticipating a market in vehicular applications for these very large format cells.

Module configuration is another topology issue. In general, the more cells that are included in each module, the fewer modules and the lower the cost of their connections. Since the number of modules must be a whole number, the number of cells per module can depend on the total number of cells necessary to reach a voltage or capacity target for the pack, and so need not be the same for every size of pack.

In the 2012 FRM analysis, battery modules for all xEVs were configured with 32 cells per module. At the time of the FRM, the Chevy Volt provided one example of a manufacturer that was already using at least 32 cells per module, in a liquid-cooled application similar to that assumed in the analysis of BEVs and PHEVs. Although most BEVs at the time had fewer than 32 cells per module, this figure was selected to represent expected improvements in cell reliability and packaging methods as manufacturers gained experience over time. It is now understood that the original Chevy Volt battery was configured with 7 modules of 36 cells each and 2 modules of 18 cells each. A similar configuration is retained in the 2016 Volt. Similarly the Kia Soul EV battery consists of 192 cells in 8 modules,[322,323] varying from 20 to 28 cells per module. As another example, in September 2015, Nissan announced the 30 kWh battery pack option available with the 2016 Leaf, in which the number of cells per module is increased from 4 to 8. The two higher-trim versions of the Leaf, the SV and SL, were the first to include the 30 kWh pack option, followed by the elimination of the 24 kWh pack option in all trims as of October 2016.[324] While the number of cells per module is still relatively small, Nissan's continued use of passive air cooling as a thermal management strategy may place a smaller limit on the number of cells per module than for the more common liquid-cooled packs that are modeled in the EPA analysis.

In November 2015 at the Tokyo Auto Show, Nissan revealed its IDS concept vehicle, powered by a newly developed 60 kWh pack.[325,326] In interviews with the press, a number of details were shared regarding the design of this pack. The pack was described as having 288 cells utilizing an NMC cathode chemistry. Assuming a nominal cell voltage of 3.75V typical of these chemistries, each cell would be sized at about 55.5 Ampere-hours, significantly larger than in the Leaf pack. The IDS pack also appears to install in a footprint similar to that of the 30 kWh version of the Leaf battery. It does not appear that Nissan has yet announced the number of cells per module in the 60 kWh pack, but appearance suggests that it is significantly larger than in the Leaf packs. One interesting aspect of the design approach for this pack is its support for a variable module stack height, suggesting a variable number of cells per module may be specified depending on the target capacity of the pack. In one press report,[327] an official was described as saying that Nissan had taken a conservative approach to the number of cells per module in earlier packs, and due to the lack of failures or other issues with those packs, were now able to consider an approach that supports a much larger number of cells per module in the new pack.

In January 2016, GM announced details of the Chevy Bolt battery pack.[328] As with the 60 kWh Nissan IDS pack, this 60 kWh pack is composed of 288 cells in 96 cell groups of 3 cells each. The cells are distributed among 10 modules, or about 28 to 30 cells per module. Three individual cells are connected in parallel at each series position. Assuming a nominal cell voltage of 3.75V, this suggests an individual cell capacity of 55.5 Ampere-hours (identical to that of the Nissan IDS pack).

As noted above, the ideal number of cells per module may vary depending on the capacity of the pack and the size of the cells. In the 2012 FRM, modules were assigned 32 cells each. This was updated to a variable number for the Draft TAR and Proposed Determination analyses, which achieves an improved optimization of the pack topology and a better targeting of pack voltage and cell capacity. More details may be found in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

2.2.4.5.3 *Usable Energy Capacity*

As previously noted in the introduction to this section, batteries may be described with respect to their gross energy capacity or their usable energy capacity. Usable capacity refers to the portion of gross capacity that the manufacturer believes can be regularly used in an application while maintaining a desired level of durability. It is thus an important parameter for battery sizing because it determines the gross capacity necessary to provide a target usable capacity for an application.

The concept of usable capacity is often accompanied by several closely related terms. In this discussion, the following terms are used and defined as follows. State-of-charge, or *SOC*, refers to the percentage of total energy (kWh) or charge (Ampere-hour) capacity that remains in a battery at a given time, ranging from 0 to 100 percent on a gross capacity basis. *SOC design window*,[329] or simply SOC window, refers to the usable portion of total capacity intended by design, expressed in terms of SOC; for example, an SOC design window might be described as the range between 25 percent and 75 percent SOC, or alternatively as an SOC window of 50 percent. *SOC swing* may be used interchangeably with SOC window but is used here to refer more specifically to observed in-use behavior rather than a design context. *Usable capacity* is thus determined by SOC design window (in a design context) or implied by an observed SOC swing (in-use). Usable capacity may refer either to a usable energy (in kWh) or the usable portion of gross capacity (in percent).

For lithium-ion chemistries, SOC is not always measurable with precision and is commonly estimated by means of algorithms that include measurements of current, voltage and battery pack temperature, both instantaneous and over time. The construct of SOC window therefore inherits some of these traits. While it is most convenient to think of the boundaries of an SOC window in terms of SOC percentages, it may also be defined by an allowable range of battery voltages, or a combination of the two.

The SOC design window that a manufacturer assigns to a battery is typically selected to balance battery durability with energy availability. Owing to the complexity of battery behavior and vehicle control algorithms, it is possible that some controllers may not refer to a single rigidly defined SOC window, but instead, may define multiple or variable SOC windows that apply to different usage conditions or are determined by the controller's observation of patterns of usage or battery health monitoring over a short or long term. For example (and particularly for HEVs), because extreme but intermittent usage conditions may have a different degree of impact on battery life than normal usage, it is possible that some manufacturers may program their controllers to define multiple target windows, to allow a wider swing to accommodate temporary, extreme conditions while following a narrower swing for normal conditions. As another example, some manufacturers may widen the allowable SOC swing as the battery ages (perhaps by allowing a wider range of allowable voltages, or modifying the allowable SOC window) in order to maintain driving range or usable capacity. Although the concept of a single SOC design window may therefore be overly simplistic for some vehicles, it remains useful for battery sizing purposes.

Setting an appropriate SOC window can be influenced by the effectiveness of the battery management system (BMS). Improved BMS systems are one potential path toward enabling a wider SOC window or a reduced battery capacity for a given range.[330]

The SOC design window is a primary factor in the sizing of a battery for a particular use. That is, the desired electric driving range for a PEV, or the amount of energy buffering capability desired for an HEV, combined with the SOC window, directly suggests the necessary gross capacity of the battery. In the 2012 FRM, for battery sizing purposes, EPA assumed a 40 percent usable SOC window would apply to HEVs, 70 percent for PHEVs, and 80 percent for BEVs.

The Draft TAR noted that increases in PHEV and BEV driving range that have been observed since 2012 may have been enabled in part by increases in SOC design window and hence usable capacity. The 2015 NAS report also stated (p. 4-5), "as extended in-use experience is obtained, the battery SOC swing may be increased for all electrified powertrains." For these reasons, in the Draft TAR EPA reviewed the usable capacity assumptions used in the 2012 FRM and made a number of revisions, as described more fully in Draft TAR Chapter 5.3.4.3.7.1. The Draft TAR analysis updated these figures to 75 percent for PHEV40, 85 percent for BEV75 and BEV100, and 90 percent for BEV200. These figures are further discussed in the paragraphs below. Applicable updates to these figures for the Proposed Determination analysis are described in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

<u>Usable capacity for HEVs</u>

For the 2012 FRM and Draft TAR analyses, a 40 percent usable capacity was chosen for strong HEVs in the 2020 to 2025 time frame. Although many production HEVs have been reported to use about 20 to 30 percent, the Draft TAR examined and reaffirmed the case for 40 percent on the expectation that improvements in battery technology and manufacturer learning would enable a wider SOC design window by 2022 to 2025.

As described in the Draft TAR, the 2015 NAS report (p. 4-5) was skeptical of the choice of a 40 percent usable capacity for HEVs and suggested using a value closer to the 20 to 30 percent observed in production HEVs. The NAS report supported this position in part by contending that, by virtually doubling the SOC window, the HEV batteries projected in the analysis would be "half the cost and size" of what would be required. However, as discussed in the Draft TAR, EPA believes that a wider SOC window would not have this effect. At the high power-to-energy (P/E) ratio of an HEV battery, cost is not as strong a function of capacity (kWh) as a function of power (kW). Therefore, reducing battery capacity from e.g. 0.50 kWh to 0.25 kWh, while holding the required power constant, would not correspondingly reduce the cost by half, because the reduction in capacity would push the P/E ratio to a higher level, counteracting much of the cost reduction. Cost projections generated by BatPaC confirm this trend and show that, for a given power capability, the cost of a 0.25 kWh pack would be very similar to that of a 0.50 kWh pack. For example, BatPaC Version 3 projects that an HEV pack sized for a power output of 15 kW would cost $634 as a 0.25 kWh pack, and $660 as a 0.50 kWh pack, a difference of only about 4 percent.[JJ] Therefore at these relative pack capacities, EPA's use of a 40 percent SOC design window for sizing purposes does not have a large impact on projected cost.

EPA also believes that developments in battery technology and manufacturer learning observed since 2012 have been consistent with the expectation that a 40 percent usable capacity will be applicable to HEVs in the 2022 to 2025 time frame. Since the 2012 FRM, numerous HEV models and battery systems intended for such vehicles have been announced. It is clear that although some HEV manufacturers have continued to use a rather conservative SOC window (for example, at AABC 2015, it was reported that the 2016 Malibu Hybrid uses a 1.5 kWh pack of which 30 percent is usable (450 Wh of 1500 Wh)[303]), there is also evidence that some manufacturers have begun increasing the SOC design window in subsequent generations of HEVs.

Specifically, recent developments in batteries for 48V mild hybrids, which have smaller batteries than strong HEVs but similarly demanding requirements, have supported a relatively wide swing. At AABC 2015, Bosch presented a 0.25 to 0.50 kWh battery system designed for use in a 48V hybrid. This battery was described as having been designed for an SOC window from 30 percent to 80 percent SOC (a 50 percent usable capacity) despite its small total capacity.[331] Also at AABC 2015, A123 Systems presented a battery system for a 48V hybrid that uses a proprietary chemistry variation on Lithium-iron phosphate which the company calls Ultraphosphate. Like the Bosch system, this 0.37 kWh pack supports a window from 30 percent to 80 percent SOC (50 percent usable capacity). A123 indicated that production of this pack is planned to begin in 2017.[301]

In 2014, EPA tested a 2013 Volkswagen Jetta Hybrid supplied by Transport Canada as part of an exploratory benchmarking exercise. Several braking and acceleration episodes were performed with the intention of eliciting maximum swing of the 1.1 kWh battery. Multiple energy swings were observed in both charge and discharge ranging from 0.56 to 0.65 kWh, equivalent to a gross SOC swing of about 51 to 59 percent.[332] Although this testing documented that the vehicle controller will permit this SOC swing to occur under these usage conditions, it

[JJ] BatPaC inputs: LMO-G chemistry, 1 module of 28 cells, EG-W (liquid) cooling, HEV-HP vehicle type, 450K annual production volume.

remains unclear whether this degree of swing would be observed regularly over normal usage. A limited amount of testing over steady-state and standard test cycles elicited smaller swings of up to approximately 30 percent. The short duration of standard test cycles and variation in the observed swing prevented firm conclusions from being drawn about the exact SOC design window the controller regularly permits.

Going forward, it is possible that improvements in cell balancing may also act to support downsizing of HEV battery sizes or widening of SOC windows from their current levels. For example, at AABC 2015, NREL presented work showing that use of active cell balancing instead of passive balancing can result in a 50 percent reduction in the necessary capacity of an HEV battery while also eliminating the need for liquid cooling.[333] Further, EPA models HEV battery costs using the liquid cooling option provided in BatPaC, which means these batteries have more effective cooling than the air cooling that currently prevails in HEV batteries, potentially allowing greater use of available capacity. HEV battery cooling is discussed further in Chapter 2.2.4.5.4 (Thermal Management).

These findings suggest that EPA's choice of 40 percent usable capacity for HEVs remains a reasonable estimate for the 2022 to 2025 time frame.

Usable capacity for PHEVs

The usable portion of total capacity for a PHEV tends to be narrower than for a BEV. One reason for this difference is that when a BEV reaches its minimum SOC, it is taken out of operation and recharged, while a PHEV instead begins to operate in charge-sustaining mode (charging and discharging within a narrow SOC band) for an indefinite time. The need to provide a proper lower-end buffer for the SOC band, and to avoid extensive operation at a very low SOC, encourages setting a higher minimum SOC point for a PHEV than for a BEV. PHEV batteries also tend to have a larger P/E ratio due to their need to provide similar power levels as a BEV battery while having a smaller capacity. A smaller SOC window would be appropriate under such conditions to promote battery life. The 2015 NAS report (p. 4-12) affirmed the FRM assumption that a 70 percent usable capacity is appropriate for a PHEV architecture.

At the time of the 2012 FRM, relatively few PHEVs were in production to serve as examples of this platform. Although the Draft TAR provided a comprehensive analysis of the PHEV models that have entered the market since, the primary production example available to inform the 2012 FRM was the Chevy Volt, which was about to be released in its first generation (referred to here as Gen1). Prior to its release, the usable capacity of the pre-production Gen1 Volt battery was commonly reported as approximately 8 kWh of a total 16 kWh, or about 50 percent. The first production Gen1 Volt is now understood to have utilized about 10.2 of 16 kWh, or about 64 percent.[334] Testing of a 2012 Chevy Volt by Argonne National Laboratory showed the vehicle to be utilizing an SOC window between 87 percent SOC and 18 percent SOC (69 percent usable capacity).[335]

The initial generations of the Chevy Volt are often described as having adopted a conservative battery management approach by utilizing a narrow SOC design window and liquid cooling. GM widened the SOC window for the Volt on at least two occasions while increasing the battery capacity on at least three. The Gen1 model was upgraded in the 2013MY from 16 kWh gross capacity to 16.5 kWh, and further increased for the 2015MY to 17.1 kWh. During this process the usable energy increased from 10.2 kWh in the 16 kWh version to 11.2 kWh in the 17.1 kWh version. This represented a small increase in usable energy capacity, from 63.75 percent of gross capacity to 65.5 percent. The Gen2 Volt, released for the 2016MY, now uses 14 kWh of 18.4 kWh gross, or about 76.1 percent usable capacity. This represents a 25 percent increase in usable capacity from the last Gen1 model.[334]

The PHEV batteries modeled in the 2012 FRM are similar to the Volt battery in that they are liquid cooled, enabling the same level of temperature control that is often cited as being responsible for the dependability of the Volt battery. The production 2016 Volt battery now exceeds the 70 percent usable capacity EPA assumed for PHEVs for the FRM analysis.

It should be noted that the 2016 Volt battery is sized for a 53 mile AER, and accordingly may have a significantly lower P/E ratio than that for a PHEV20. This may allow it to enjoy a wider SOC design window than the smaller battery of a PHEV20 or possibly even that of a PHEV40. Therefore, the Volt example may not by itself be conclusive that a wider SOC window would be appropriate for PHEV20 or PHEV40. However, according to results of testing at Argonne National Laboratory, the Ford Fusion Energi utilizes about 5.9 kWh of its 7.6 kWh gross capacity, or about 78 percent. This provides an additional data point suggesting that a wider SOC window than 70 percent may be appropriate even for some shorter-range PHEVs. The Fusion Energi is rated at 20 miles of AER, and utilizes a blended depletion style that may utilize the engine if driven more aggressively than in the standard EPA test cycles. This engine supplementation at elevated power demands is likely to result in lower peak power demands on the battery, potentially making wider swings less demanding on the battery.

For the 2012 FRM, a 70 percent usable capacity had been chosen to represent both PHEV20 and PHEV40 vehicles. As discussed in the Draft TAR, the findings reviewed above suggested that a 70 percent usable capacity for PHEVs may have been a conservative estimate for the 2022 to 2025 time frame. The Draft TAR therefore updated the PHEV40 usable capacity to 75 percent. EPA has further reviewed PHEV usable capacities for the Proposed Determination analysis, and has updated these estimates as described in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

<u>Usable capacity for BEVs</u>

The Draft TAR examined the large number of BEV models that had reached production since the 2012 FRM. Further activity in the industry has provided abundant opportunity for manufacturers to begin drawing conclusions regarding the appropriateness of the SOC design windows they chose to implement in their first generation models, and even to begin applying the findings to subsequent model generations. It has also provided many opportunities for research organizations to test these vehicles to ascertain aspects of their design and behavior, including SOC swings observed in use. Table 2.6 summarizes some estimated SOC swings observed in 2012-2016MY BEVs, which are further described below.

Table 2.6 Estimated SOC swings for selected MY2012-2016 BEVs

Example	Estimated SOC swing	Source
ANL BEV benchmarking (various)	80 to 90 percent	Argonne National Laboratory

Tesla Model S 85	85 percent	AVL
2015 Kia Soul EV	90 percent	Idaho National Laboratory
BMW i3	87 percent	Idaho National Laboratory

Argonne National Laboratory (ANL) operates an ongoing research program to benchmark xEVs.[335] Vehicle testing from multiple instrumented battery electric vehicles has shown that the vehicles operate usable SOC windows ranging from 80 percent to 90 percent whether air cooled or water cooled.[KK]

At AABC 2015, AVL presented the results of a teardown of a Tesla Model S battery pack.[289] AVL reported that cycling tests of the pack suggested that 73 kWh of the 85 kWh gross capacity is accessible, suggesting that this pack may be utilizing an 85 percent usable capacity. This result is in line with reports from Model S owners that have suggested a usable capacity of about 75 to 76 kWh.[336]

The Advanced Vehicle Testing Activity group at Idaho National Laboratory has tested the batteries of several BEVs currently in production.[337] In testing of the 2015 Kia Soul EV, the measured battery capacity ranged from 30.4 to 30.5 kWh in each of four test vehicles. The service manual for the 2015 Kia Soul EV is reported to list a nominal SOC range of 5 percent to 95 percent, or 90 percent usable, for the high voltage battery system.[338] A 90 percent SOC window would amount to about 27 kWh of usable energy, the same as Kia advertises. In a departure from the practice of most other OEMs, Kia may be advertising the usable capacity rather than the gross capacity.

Technical specifications for the BMW i3 indicate a battery capacity of 18.8 kWh.[339] Numerous press sources widely repeat this figure as a usable SOC while consistently citing a gross SOC of 21.6 kWh or 22 kWh. The 21.6 kWh figure is highly consistent with the results of battery testing by Idaho National Laboratory[340,341,342,343] for four 2014 BMW i3 vehicles under test, which indicated gross capacity ranging from 21.4 kWh (one vehicle) to 21.7 kWh (three vehicles). Like Kia, BMW appears to be advertising the usable capacity of the i3 battery rather than the gross capacity. A gross capacity of 21.6 kWh suggests a usable capacity of 87 percent.

In May 2014, the Chevy Spark EV underwent changes to its battery that may indicate a widening of SOC design window. In announcing a change in cell supplier from A123 Systems to LG Chem, General Motors also indicated that the new Spark battery would be reduced in capacity from 21 kWh to 19 kWh, while keeping the same range of 82 miles and the same mpge.[344] Given that rated mpge did not change, this suggests that retention of the original range was more likely made possible by widening the SOC design window than by increasing powertrain efficiency. A widened window could be enabled by either the use of a different battery chemistry (going from A123's Lithium-Iron Phosphate to LG Chem's NMC+LMO chemistry), and/or an increased comfort level due to ongoing experience with the platform. Since the original A123 cathode chemistry (Lithium-Iron-Phosphate or LFP) is comparable to

[KK] Instrumented battery electric vehicles include: 2015 Chevrolet Spark EV, Kia Soul EV, 2014 Smart EV, 2013 Nissan Leaf, 2012 Ford Focus Electric.

LG Chem's LMO-dominant chemistry in terms of allowable SOC swing, it suggests that experience may have played at least some role in this change.

At AABC 2015, Honda reported that their decision to extend the lease option on the Fit EV by 2 years was based on learning that the batteries in these vehicles were experiencing lower degradation than projected.[345] This suggests that it might be possible to widen the SOC design window in future releases while maintaining durability targets.

For the 2012 FRM, an 80 percent usable capacity was assigned to BEV batteries. This was based on knowledge of manufacturer plans as well as examples seen in the press for early production BEVs such as the Nissan Leaf and other developmental vehicles. The 2015 NAS report (p. 4-12) affirmed that an 80 percent usable capacity is appropriate for BEVs. These observations of industry practice may be compared with EPA's 2012 choice of 80 percent usable capacity for all BEVs. The Draft TAR found that a usable capacity of about 85 percent for BEV75 and BEV100, and 90 percent for BEV200, were more appropriate to assess. EPA further reviewed these figures for the Proposed Determination analysis, and concluded that they are still appropriate, as described in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

2.2.4.5.4 Thermal Management

Battery thermal management includes battery cooling to reject heat generated during use, and in many cases battery heating to warm the battery in cold weather. In systems where active thermal management is present, the battery management system (BMS) will work to keep the battery within a preferred temperature range during use.

Battery thermal management systems are commonly divided into passive systems (where the outside of the pack is exposed to ambient air) and active systems (where a cooling medium is circulated through the pack, or thermoelectric components are integrated with the pack). Active cooling media may be ambient air, cabin air, air conditioned by the vehicle A/C system, a liquid coolant, or the A/C system refrigerant.[346,347,348,349]

For the FRM and Draft TAR analyses, EPA assumed all PEV packs would employ active liquid cooling, as seen in production vehicles such as the Chevy Volt and in several other PEVs. In contrast, the FRM analysis assigned passive air cooling to HEV packs. This was updated to active liquid cooling for the Draft TAR analysis.

One recent approach to cooling battery packs involves placement of a bottom cooling plate beneath the packaged battery cells rather than between each cell. Coolant or refrigerant circulates through the plate and cools the battery cells conductively. This approach is used in the BMW i3 battery, was once used in the Chevy Spark A123-supplied battery, and is possibly being used in the Chevy Bolt pack.[350]

Direct circulation of refrigerant rather than an intermediary fluid such as a glycol-water mix can also improve heat rejection and vehicle packaging by eliminating the secondary cooling loop that would otherwise be needed to reject heat to the atmosphere. The BMW i3 utilizes refrigerant cooling.[346]

Active liquid cooling continues to be the predominant thermal management method for the battery packs of BEVs and PHEVs announced since the FRM. The notable exception is the Nissan Leaf, which continues to use passive air cooling as it has since its first generation. At the time of the FRM, some in the industry and press were expressing skepticism about Nissan's choice of passive air cooling.[351,352,353] Some customers had also begun reporting unexpected battery degradation in hot climates such as Arizona, which some attributed to inadequate thermal management. During the 2014 MY, Nissan adjusted the chemistry of the battery pack to better withstand high temperatures.[354] Although Nissan has continued to use passive air cooling in the 2016 Leaf (and also in the new 60 kWh pack under development), all other production BEV and PHEV packs introduced since the FRM use some form of liquid or refrigerant-based cooling. The 2015 NAS report (under "Cooling," p. 4-17) tended to affirm the agencies' assumption of liquid cooling for BEV packs by independently noting the potential inadequacy of passive air cooling in the Leaf pack.

Although HEV packs were modeled with passive air cooling in the 2012 FRM analysis, the Draft TAR noted some evidence that even these packs may be moving toward liquid cooling, and adopted liquid cooling in that analysis partly for that reason and partly due to practical considerations with the BatPaC model, as described in the Draft TAR Chapter 5.3.4.3.7.1. Although air cooling continues to predominate in HEV packs,[349] a presentation by Mahle at TMSS 2015 suggests that air cooling is increasingly being displaced by liquid cooling even in HEV packs.[347] Johnson Controls has also described a 260 V, 1.7 kWh HEV battery product with provision for liquid cooling.[355] Effective cooling and heating capability is often cited as a potential path toward reducing the size of xEV batteries by allowing more of their capacity to be utilized while avoiding the degradation that otherwise might result from heating.[349,341] This suggests that liquid cooling may become one of the enablers for future HEV batteries to provide the 40 percent usable capacity EPA assumes in this analysis.

As previously described, EPA uses ANL BatPaC to model the cost of xEV batteries, including mild and strong HEV batteries. BatPaC provides cost estimates for several cooling options, including active air cooling (cabin air or cooled air) and liquid cooling (glycol/water mix). It does not model passive air cooling without air channels between the cells, as might be found in passively cooled HEV batteries. For the Draft TAR analysis, EPA performed several trials to investigate the impact of the available cooling choices for HEV batteries, and found that BatPaC assigns similar or slightly lower costs for its implementation of liquid cooling than for its implementation of active air cooling. For these reasons EPA adopted the liquid cooling option under BatPaC to model the cost of HEV packs for the Draft TAR analysis as well as the Proposed Determination analysis, as already true for PHEV and BEV packs.

2.2.4.5.5 Pack Voltage

Some of the HEV battery packs EPA studied for the 2012 FRM operated at approximately 120V. This relatively low voltage (as compared to PHEVs and BEVs) has some advantages, such as being compatible with the use of a relatively small number of cells per pack, and reducing the voltage step between the high-voltage system and the 12V electrical system that typically remains in these vehicles. In contrast, some HEVs use a higher voltage more typical of PHEVs or BEVs, which may have the advantage of being more compatible with the voltage ranges of available power electronics components, or the desired power output of the battery to fulfill its role as part of the system.

Larger packs for PHEVs and BEVs are typically composed of a large number of cells and so can reach almost any voltage level desired. While safety considerations continue to place a practical upper limit on system voltage, a moderately high voltage is consistent with the greater power flows required by these vehicles and offers the added benefit of conducting energy at a lower amperage, which reduces the necessary weight and cost of electrical conductors and reduces I^2R losses. Compatibility of available supplier parts may also encourage different manufacturers to target a similar voltage envelope. Many manufacturers of PHEVs and BEVs appear to have targeted the range between 300V and 400V.

In general, the system voltages EPA chose for modeling xEVs were based on those seen in production xEVs at the time of the FRM. Accordingly in the 2012 FRM and Draft TAR analyses, EPA limited pack voltages to certain ranges depending on whether the pack was intended for an HEV, PHEV, or BEV. HEVs were targeted to about 120V while PHEVs and BEVs ranged from about 300V to 400V.

Originally, in the 2012 FRM analysis, a 600V upper limit on BEV battery voltage had been applied to the largest BEV packs. At the time of the 2012 FRM, VIA Motors had been producing a plug-in electric truck with a 650V battery pack. However, later versions of this and other VIA products by the time of the Draft TAR had adopted a lower battery voltage of around 350V to 380V, suggesting that some advantage was seen to adopting a lower voltage. The Draft TAR analysis therefore reduced the 600V limit to about 400V, which is retained for the Proposed Determination analysis.

Other examples of PHEVs and BEVs in the 600V region exist as past-production or concept vehicles. The McLaren P1 PHEV, first introduced to the U.S. in 2014 as a very limited production high-performance vehicle, operated at 535V, but is no longer in production. In September 2015, Porsche announced the Mission E concept BEV that would operate at 800V. The higher voltage was described as enabling much faster charging as well as lower conductor weight.[356] However, this vehicle has not yet been introduced. These examples suggest that voltage ranges of 600V or greater may continue to be applicable at least to high performance BEVs and PHEVs, even though they are largely not present in the market today.

For this Proposed Determination analysis, EPA has determined that the targets of 300V-400V for PHEVs and BEVs remain appropriate (as described in detail in Chapter 2.3.4.3.7).

Public comment on the Draft TAR analysis from Toyota questioned the use of 120V for HEVs. Although it is true that some HEVs are currently targeting voltage ranges higher than 120V, increasing the voltage of a small (approximately 1 kWh) pack to several hundred volts requires a larger number of relatively small cells, at a higher potential cost. Going forward to the 2022 to 2025 time frame, it is unclear whether the advantage of operating an HEV at a higher voltage will continue to outweigh the higher cost of the battery. Therefore, EPA has retained the approximately 120V target for modeled high-voltage HEVs. More discussion of this comment and the target voltages for HEVs and PEVs in the Proposed Determination analysis is found in Chapter 2.3.4.3.7.4 (Assumptions and Inputs to BatPaC).

2.2.4.5.6 Electrode Dimensions

The electrodes of a lithium-ion cell are in the form of flat foil strips coated with active materials and stacked or rolled together. Several important parameters of cell performance are controlled by the dimensions of the electrode; in particular, the thickness of the active material coatings on the electrodes and the aspect ratio (length-to-width ratio) of the electrodes.

In general, thinner electrode coatings promote power density, while thicker coatings promote energy density. By default, BatPaC limits coating thickness to no less than 15 microns and no more than 100 microns due to various practical considerations.[135] The lower limit represents interfacial impedance effects associated with very thin electrode coatings.[357] The typical precision of coating equipment, at around plus or minus 2 microns,[358] would also become challenged below this thickness. The upper limit represents material handling and ion transport considerations. Thicker coatings may be prone to flaking when uncut electrode sheets are rolled or unrolled for shipment and processing. Thicker electrodes also require ions to travel a greater distance through the active material during charge and discharge, leading to effects such as increased resistance, reduced power capability, and the potential for lithium plating on charging. In the 2012 FRM and Draft TAR analyses, electrode coating thickness was therefore limited to 100 microns. In practice, this limit was only encountered by the most energy intensive packs for large BEVs.

As discussed in the Draft TAR, updates to BatPaC between the FRM and Draft TAR included improvements to the model by which electrode thickness is determined. In most cases this resulted in somewhat thinner electrodes than would have been projected in the version used for the 2012 FRM analysis. This resulted in a slightly higher cost per kWh for most battery packs, all other things being equal.[359]

Electrode aspect ratio is another important parameter, because it determines how far current must travel on average between where ions reside in the active materials and the current collector tabs. Longer distances are associated with greater resistance and heat generation. If the length is much greater than the width, and the current collector tabs reside on the short dimension rather than the long dimension, current must travel farther on average than in the inverse situation. BatPaC assumes a default aspect ratio of 3:1, with tabs placed on the short dimension. In the 2012 FRM, EPA had used an aspect ratio of 1.5:1, loosely based on the dimensions of some commonly known cells at the time.

As originally discussed in the Draft TAR, the 3:1 default aspect ratio used in BatPaC appears to be seeing increasing use in the industry. In announcing the 200-mile Chevy Bolt EV[328] at the 2016 NAIAS, GM indicated that its battery cells, supplied by LG Chem, have an aspect ratio of 3.35:1 (measuring 3.9 inches by 13.1 inches). An animation accompanying the announcement shows that the cell tabs reside on the short dimension. GM describes this aspect ratio as "landscape format," presumably to highlight the low-profile design of the pack that allows the entire pack to reside within the floor space of the vehicle. The Kia Soul EV battery also uses cells with a nearly identical aspect ratio and tab placement, supplied by SK Innovation.[360,298]

Also at the 2016 NAIAS, Samsung SDI introduced a family of cells ranging from 26 to 94 Ampere-hours,[361] some of which have a similar aspect ratio to the GM Bolt cells but with tabs on the long dimension. Samsung also displayed a line of "low height packs," suggesting that it anticipates a trend toward low-profile applications for which these cells would be well suited.[362] In December 2015, Volkswagen also announced plans to pursue flat, low-profile pack designs for future electrified vehicles,[363] which likely will also call for a similar cell aspect ratio.

These examples lent support to the validity of the default 3:1 aspect ratio and tab placement assumed by BatPaC, and EPA therefore adopted a 3:1 aspect ratio for the Draft TAR analysis.

No public comment or new information suggested changing the targets for aspect ratio or electrode thickness for this Proposed Determination analysis. As described in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs), the Proposed Determination analysis retains the Draft TAR values for these parameters.

2.2.4.5.7 Pack Manufacturing Volumes

In the 2012 FRM analysis, EPA assumed that battery pack manufacturing would reach full economy of scale at an annual production volume of 450,000 packs in the year 2025. This volume was based on the annual manufacturing volumes assumed by FEV in the teardown analyses performed for the FRM analysis.

In BatPaC, when the user specifies a production volume of 450,000 for a given battery pack, it means that the cost estimate for that specific pack is based on a dedicated manufacturing plant that manufactures an annual volume of 450,000 of that identical pack. Since all of the packs produced by the hypothetical plant are identical, it implies that the cost estimate is most applicable to a situation in which the packs are intended to be used by a single manufacturer in a single model of electrified vehicle.

The 2015 NAS report noted (p. 4-42, and Finding 7.3, p. 7-23) that the technology penetration levels projected by the agencies for electrified vehicles are lower than the 450,000 annual production volume that the agencies assumed in projecting battery pack costs for the 2022 to 2025 time frame. Further, it noted that whatever annual production did occur would likely be divided among multiple manufacturers and multiple models, preventing the full economy of scale of 450,000 units from being achieved by any single manufacturer. The report recommended that the agencies use a smaller manufacturing volume for electrified vehicle battery packs to better reflect projected technology penetration, rather than the 450,000 annual production assumed in the 2012 FRM.

Despite EPA's use of an annual production of 450,000 units, it is unclear whether this results in more optimistic estimates of battery cost than the industry may realize. The following discussion describes several points relevant to this consideration: (a) the potential for a "flex plant" manufacturing approach to realize economy of scale at much lower pack volumes; (b) the potential for economies of scale to fully develop at production volumes at low as 60,000; (c) examples of actual costs that are already lower than EPA's FRM estimates at a much lower production volume than 450,000; (d)EPA's placement of estimated costs in the year 2025 instead of 2020; and (e) the potential for consolidation in the battery industry to increase pack manufacturing volumes.

There is evidence that optimizing the approach to battery manufacturing by adopting a "flex plant" approach may allow economies of scale to be realized at pack production volumes much lower than 450,000. According to a recent ANL study,[364] a battery manufacturing plant that is designed to simultaneously manufacture packs for multiple vehicle types (HEVs, PHEVs and BEVs) by standardizing on a single electrode width can significantly reduce the pack manufacturing volumes required to achieve maximum economy of scale. The ANL study calls this approach a "flex plant." Some manufacturers already appear to be adopting a similar approach for production of prismatic cells. For example, at AABC 2015, Samsung SDI described a strategy to build an "ecosystem" of xEV battery products by maintaining a "standard cell format between generations," that is, by maintaining the same cell dimensions and container size and achieving different target capacities by varying the chemistry.[321] At the same conference, Bosch similarly described a goal to produce packs of varying capacity by use of a standard 36 Ampere-hour cell.[331] XALT Energy also described its practice of achieving variable cell capacity (Ampere-hour) sizes by adjusting the electrode count within a cell while maintaining one of two fixed cell footprint areas.[365] Cell standardization also may promote the economics of battery second life applications[366] and so could provide an added motivation for manufacturers to reduce the number of cell formats. EPA anticipates that the most successful suppliers may continue to adopt similar approaches over time. As this occurs, the production volume of the individual cells that compose the several pack types produced from those cells would increase dramatically, even though pack volume of any single pack type may remain relatively low. This increased cell volume may recapture much of the economy of scale reflected at the pack level in the 450,000 unit assumption.

There is also some evidence to suggest that economies of scale may be achieved at much smaller pack production volumes than 450,000, even without necessarily adopting a flex plant approach. According to the ANL flex plant study, the benefits of a flex plant over a dedicated plant for reducing the cost of BEV batteries levels off past a production level of about 60,000 units per year, suggesting that 60,000 units would approach maximum economy of scale for a dedicated plant. The 2015 NAS report (p. 4-42), in noting that the agencies' projected costs for 2012 "seem reasonable" despite the large volume assumed, cites as a possible explanation a TIAX study (referred to as Sriramulu & Barnett 2013 in a National Research Council report on Overcoming Barriers to EV Deployment[243]) that also suggests a 60,000 unit volume at which economies of scale would be realized. This level of production is much closer to the technology penetration levels EPA predicts. Individual manufacturers such as Nissan and Tesla are already approaching similar production levels, with Nissan having sold more than 30,000 Leaf EVs in North America in 2014, and Tesla projecting a similar amount in 2015. The BMW i3 and i8 PHEVs are also approaching a global production level of 30,000 units per year.

There is also evidence that actual battery pack costs experienced by some manufacturers are already lower than EPA's FRM estimates, at a much lower production volume than 450,000. As discussed in more detail below, General Motors has cited its rapidly falling battery cell costs from supplier LG Chem as evidence of their being "able to achieve lower costs earlier with much less capital and volume dependency" than presumably had been expected. The cell-level costs cited by GM for the Chevy Bolt are lower than the BEV pack costs projected by the agencies in 2012. Because it appears to suggest a currently contracted price applicable at the very beginning of the Bolt product cycle, it therefore is likely to be based on an annual production level of far less than 450,000 packs. Production of the 2017 Bolt has been characterized as capable of serving a demand of around 50,000 units per year.[367]

The way EPA applies the BatPaC-generated costs also treats them conservatively. Although the cost estimates generated by BatPaC are intended by its authors to represent technology being used in the year 2020, EPA assigns these costs to the year 2025 when applying reverse-learning to generate year-by-year cost estimates for earlier years. Although this was a practical choice in order to cover the full time frame of the standards which run to MY2025, it has the effect of making the projected costs more conservative by assuming that the technology projected by the BatPaC authors will not take effect for an additional five years.

Consolidation among battery cell suppliers may also improve the ability for individual suppliers to begin approaching the production volumes assumed in the analysis. Since the FRM, there has been significant consolidation among battery manufacturers.[368,369,370] For example, A123 Systems, which at one time competed against LG Chem to supply battery cells for the Chevy Volt and was later chosen to supply the Fisker Karma and Chevy Spark, filed for bankruptcy in late 2012 and was sold to Chinese auto supplier Wanxiang in 2013.[371] Wanxiang has since refocused A123's efforts toward smaller HEV and stop-start batteries as well as grid storage. Johnson Controls, which was ranked in second place as an industry leader by one analysis firm in 2013,[370] also has refocused its effort on smaller batteries. As of late 2015, three xEV cell suppliers appear to have been particularly successful at developing OEM partnerships: LG Chem, Panasonic, and Samsung SDI.[372] LG Chem has grown its customer list to include not only GM but also Renault, Volvo, Daimler, Volkswagen, Audi, and Tesla.[373] Panasonic is also a dominant player through its ongoing partnership with Tesla, as well as supplying smaller contracts with Ford and Volkswagen. Samsung SDI is a supplier to BMW and in 2015 announced plans to acquire the battery division of Magna International.[374] Nissan's joint-venture arm Automotive Energy Supply Corporation (AESC) is also an important player through its battery production for Nissan and Renault vehicles, including the Nissan Leaf. In 2015 it was reported that Nissan is also considering a partnership with LG Chem for its future BEV batteries.[375] Even Tesla, which has long-term plans to source cells from its so-called Gigafactory, is said to be investigating the possibility of sourcing cells from other leading suppliers in order to meet expected demand for the Model 3 in a timely manner.[376]

As discussed in the Draft TAR, EPA believes that an assumed manufacturing volume of 450,000, as a BatPaC input, is appropriate for the purpose of generating battery pack cost estimates applicable to the 2022 to 2025 time frame.

Some public comments on the Draft TAR addressed EPA's manufacturing volume assumptions in the Draft TAR analysis. Comments on this topic are were considered and are addressed in Chapter 2.3.4.3.7.4 (Assumptions and Inputs to BatPaC).

2.2.4.5.8 Potential Impact of Lithium Demand on Battery Cost

At circa-2010 prices, the cost of lithium content was said to be only about 1 percent of total material cost at the battery pack level[377] or perhaps 2 percent at the cell level.[378] Lithium comprises a similar percentage by mass, and at time of manufacture resides primarily as ions in the cathode active material and the electrolyte solution.

Lithium used in cell manufacturing is most commonly sourced as lithium carbonate.[379] Lithium carbonate is primarily recovered from ancient continental brines underlying salt lake deposits. These are widespread in the southern Andes (primarily Bolivia, Argentina, Chile) and western China and Tibet, with deposits identified in the southwest United States as well. Brine mining operations are found or are under development in many of these areas. Lithium may also be recovered from some oilfield brines in the western U.S. Some lithium is also recovered from hard-rock deposits, particularly in Australia. [380,381]

Controversy has periodically arisen about the adequacy of known lithium reserves to service the potential demand generated by the electrified vehicle industry. Because industrial applications for lithium were relatively few and scattered prior to its use in batteries, known reserves may not be as well enumerated as for other commodities, and may have potential to increase as demand increases and previously unidentified or unexploited sources are recognized. Recently, concerns about lithium prices have been renewed by a significant increase in the price of lithium, thought to be resulting in part from increased demand for use in electrified vehicles.[382,383] Pressure also appears to be increasing on manufacturers to secure lithium sources that will be needed to supply increased production capacity.[384]

However, lithium appears to be plentiful enough at this time to suggest that its availability will not be a constraint in the near term.[385,386] A study released by Carnegie-Mellon University in May 2016[387] addressed this issue directly by examining the sensitivity of battery cell manufacturing cost to the price of lithium carbonate and lithium hydroxide. The study concluded that the effect on battery pricing would be minimal (never more than 10 percent) even for the most extreme lithium price fluctuations considered (about four times the historical average). The researchers also suggested that the primary difficulty imposed by such fluctuations would be felt by cell manufacturers in maintaining profit margins, rather than by vehicle manufacturers or consumers. Development of new lithium resources is being actively undertaken in many areas across the world.

2.2.4.5.9 Evaluation of Draft TAR Battery Cost Projections

As described in the Draft TAR, EPA has adopted a bottom-up, bill-of-materials approach to projecting the future DMC of xEV batteries by using the ANL BatPaC battery cost model.[135] As discussed in the Technical Support Document (TSD) accompanying the 2012 FRM,[388] battery pack costs projected by this model were shown to compare favorably with cost projections provided by suppliers and OEMs that were interviewed during development of the rule. In the 2015 NAS report (Finding 4.4, p. 4-43), the committee found that "the battery cost estimates used by the agencies are broadly accurate," providing further support for the use of this model.

The Draft TAR examined several sources that had emerged since the FRM that provide additional information on the evolution of battery costs and potential future trends.

In 2015, a peer-reviewed journal article (Nykvist and Nilsson, 2015) appeared that provides a comprehensive review of over 80 public sources of battery cost projections for BEVs.[153] Based on a statistical analysis of these estimates, it was shown that industry cost estimates for lithium-ion batteries for BEVs have declined 14 percent annually between 2007 and 2014, and that pack costs applicable to leading BEV manufacturers have followed a cost reduction curve of about 8 percent per year, with a learning rate of between 6 percent and 9 percent. The authors concluded that the battery costs experienced by market leading OEMs are significantly lower than previously predicted, and that battery costs may be expected to continue declining.

In Figure 2.36, the full population of cost estimates reviewed by Nykvist and Nilsson is compared to the battery pack cost projections of the Draft TAR analysis. Because BatPaC does not produce cost estimates for multiple years, the OMEGA analysis applies a learning curve to generate costs for the years 2017 through 2025, with BatPaC output costs assigned to the year 2025. The learning-adjusted costs shown in the figure include those for PHEV40, BEV75, BEV100, and BEV200 (Draft TAR). These vehicle types have relatively large battery capacities similar to those included in the review. The plot shows that the battery costs per kWh projected in the Draft TAR (shown as green circles) fit well with the reviewed estimates (orange squares), and lie on a similar cost reduction curve.

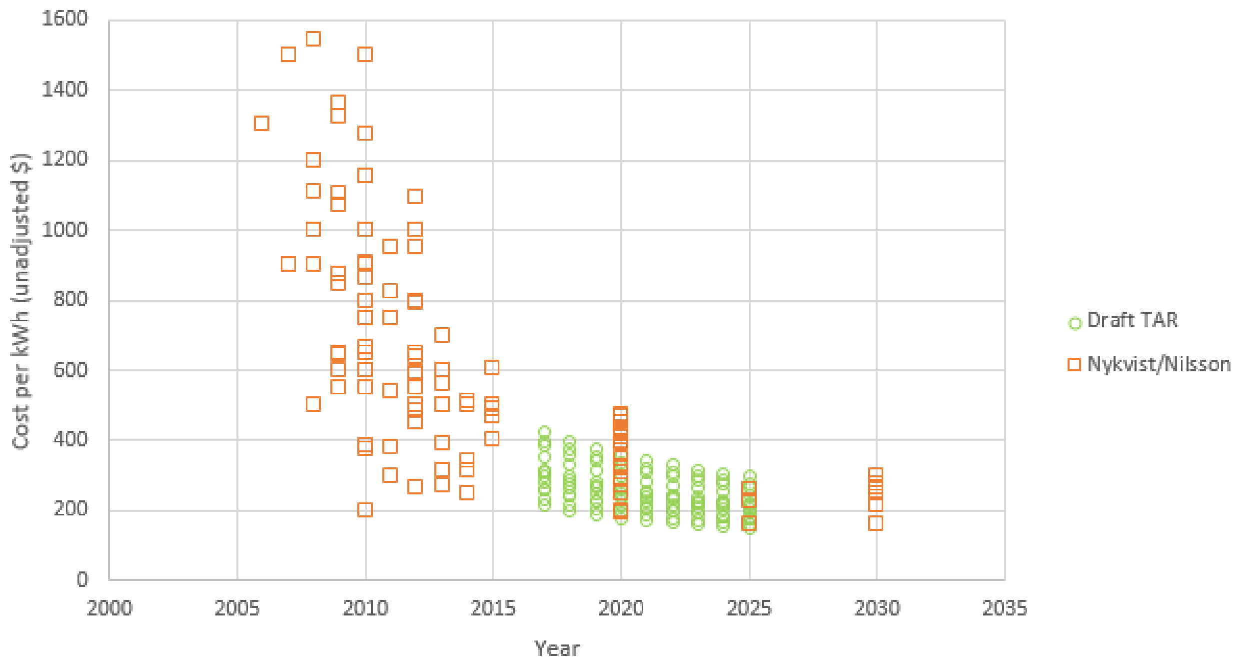


Figure 2.36 Comparison of Draft TAR Projected Battery Cost per kWh to Estimates Reviewed by Nykvist & Nilsson

Cost estimates and projections are most useful when they can be validated by comparison to actual costs. Unfortunately, information about actual battery costs being paid or under contract by manufacturers for production vehicles is rarely disclosed publicly. However, when General Motors publicly commented on its battery costs for the Chevy Bolt EV (a BEV200) in October 2015, it provided a valuable opportunity to evaluate the 2012 FRM projections of BEV200 battery costs, as well as those projected by the Draft TAR analysis.

General Motors held its Global Business Conference on Oct. 1, 2015, where various speakers described to an investor audience its current development status and plans with regard to various advanced vehicle technologies. In a presentation on electrification, GM disclosed its projected cost per kWh (on a cell basis) for battery cells for the Chevy Bolt EV. Citing partnership with cell manufacturer LG Chem, Executive Vice President of Global Product Development Mark Reuss stated, "When we launch the Bolt, we will have a cost per kWh of $145, and eventually we will get our cost down to about $100. We believe we will have the lowest cell cost with much less capital and volume dependency."[389] An accompanying chart shows the $145 cost continuing to 2019, dropping to $120 per kWh in 2020 and to $100 per kWh in 2022.[390,391]

It is important to note that the costs described above are cell-level costs and not pack-level costs. To compare them to the pack-level costs that EPA projects in this analysis requires converting them to that basis using an appropriate methodology. Also, although the context of the announcement suggests that the costs are comparable to a direct manufacturing cost, their exact basis is unknown. Although these factors introduce some uncertainty in comparing the announced costs to the EPA projections, a qualified comparison is possible.

Several sources exist that suggest a cost conversion factor from cell-level costs to pack-level costs for lithium-ion batteries.[392,316,289,393,394,395] These are summarized in Table 2.7. Most of these sources suggest a conversion factor of about 1.25 to 1.4.

Table 2.7 also includes two estimates that EPA derived from the ANL BatPaC model for a liquid-cooled BEV-sized pack at a production volume of 50,000 to 100,000. Outputs from this model suggest that the ratio of pack-level cost to cell-level cost for the pack format modeled by BatPaC may range from about 1.5 for a 16 kWh pack to about 1.3 for a 32 kWh pack, and continuing to decrease for larger pack capacities.

Table 2.7 Examples of Conversion Factors for Cell Costs to Pack Costs

Source	Low	High
Kalhammer et al.[392]	1.24	1.4
Element Energy[316]	1.6	1.85
Konekamp[289]	1.29[LL]	
USABC[393]	1.25[MM]	
Tataria/Lopez[394]	1.26[NN]	
Keller[395]	1.2[OO]	
BatPaC, 16 kWh	1.5	
BatPaC, 32 kWh	1.3	

On the basis of the BatPaC-derived ratios of 1.3 to 1.5, the 2015-2019 cell-level figure of $145 per kWh would translate to approximately $190 to $220 per kWh on a pack level. The future projections of $120 and $100 per cell kWh in 2020 and 2022 would translate to approximately $156-$180 per kWh and $130-$150 per kWh at the pack level, respectively. On this pack-converted basis the GM cell costs agree well with the BatPaC cost projections (which the Draft TAR analysis applies to 2025).

Table 2.8 compares the estimated pack-level equivalents of the GM cell costs to the projected BEV150/200 pack-level costs of the 2012 FRM and Draft TAR analyses. The pack-converted GM projection (for 2020), at $156-$180 per kWh, compares well to the Draft TAR costs for BEV200 (for 2025), which ranged from $160 to $175 per kWh. Similarly, even though the Draft TAR projected costs are significantly lower than the FRM projected costs, they are very similar to the GM pack-converted costs for 2022. Assuming that the GM pack-converted costs are reasonably comparable to the EPA projected costs, this tends to support the Draft TAR projections. Further, it should be noted that the EPA costs are projected using an annual volume of 450,000 units and are attributed to the year 2025. This tends to make the EPA projections more conservative, because the GM figures are supposed to be achieved in earlier years, and are likely to be predicated on much smaller annual production volumes.

[LL] Cell cost = 620 Euros*16 modules = 9,920 Euros; pack cost = 12,800 Euros; 12,800/9,920 = 1.29.

[MM] USABC 2020 goals for advanced EV batteries cite a cost of $125/kWh at pack level and $100/kWh at cell level = 1.25.

[NN] For a 40 kWh pack, cell costs estimated at $258/kWh; pack-related costs at $2,626, or $66 per kWh; (258+66)/258 = 1.26.

[OO] Cites one goal of 21st Century Truck Partnership as "Cost of overall battery pack should not exceed cost of the cells by more than 20% by 2016" (slide 6).

Table 2.8 Comparison of GM/LG Chem Pack-Converted Cell Costs to FRM BEV150 Pack Cost

		Pack Cost/kWh (2015$)	
Source of Estimate	Year Applicable	Low	High
BEV150 in FRM	**2025**	**$160**	**$175**
BEV200 in Draft TAR	**2025**	**$120**	**$160**
GM/LG Global Business Conference	2015-2019	$190	$220
	2020	**$156**	**$180**
	2022	**$130**	**$150**

Figure 2.37 compares the pack-converted GM costs to the year-by-year learning-adjusted costs used in the 2012 FRM and Draft TAR for Small, Standard, and Large Car BEV150 and BEV200. It can be seen that the range of the pack-converted GM costs (solid orange lines) is much lower than the costs predicted by the 2012 FRM analysis (solid gray dots). The costs projected for the Draft TAR analysis (blue circles) are much closer to the pack-converted GM costs, and in some cases intersect with the line representing a 1.5x cell-to-pack conversion factor. Based on the BatPaC-derived conversion factors for large BEV packs, the 1.3x line is probably a more representative estimate than the 1.5x line due to larger pack size. All of the Draft TAR estimates are above the 1.3x line, suggesting that the Draft TAR projections continue to be conservative relative the pack-converted GM costs. Of course, it is uncertain whether the GM costs are directly comparable because it is unknown to what extent those costs represent direct manufacturing costs output by BatPaC. However, with these qualifications, this comparison provides a valuable perspective on the Draft TAR projected costs for EV200.

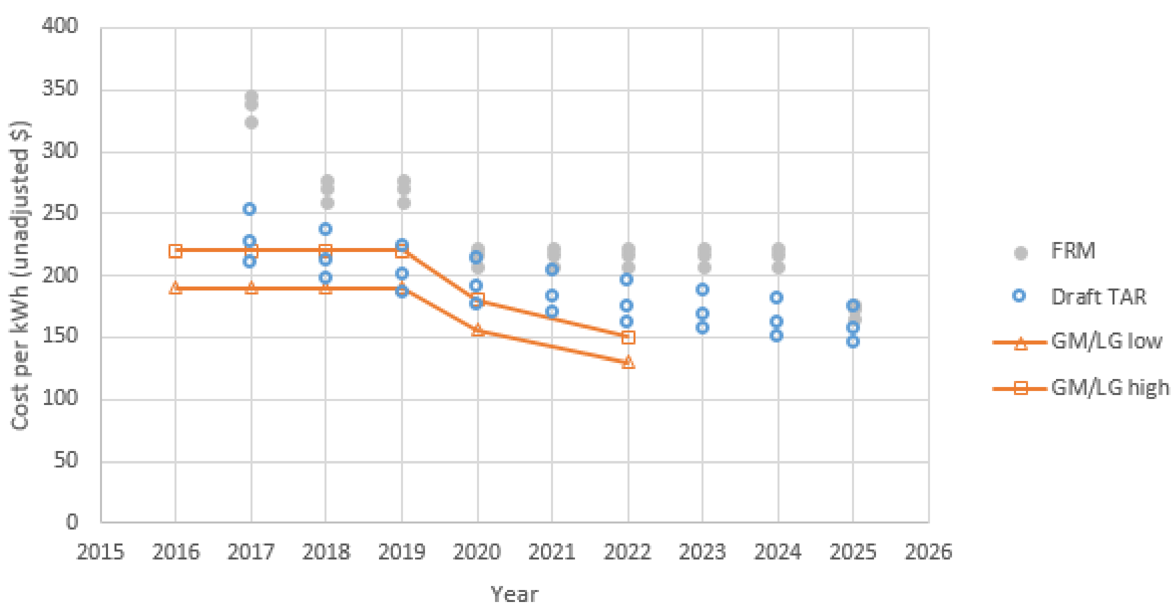


Figure 2.37 Comparison of Estimated GM/LG Pack-Level Costs to 2012 FRM and Draft TAR Estimates for BEV150/200

As discussed in the Draft TAR, at the time of the FRM, EPA's battery cost estimates appeared to be lower than costs being reported by many suppliers and OEMs at the time, and also lower than some independent estimates said to be applicable to the time frame of the rule. EPA chose to place confidence in the peer-reviewed ANL BatPaC model due to its rigorous, bottom-up approach to battery pack costing, and the expertise of leading battery research scientists that contributed to its development. The comparisons described above suggest that this approach was effective and may in fact have been conservative not only with respect to characterizing the pace of reductions in battery cost that have taken place in the time since the FRM but also to projecting future costs for the 2020 to 2025 time frame. Up to and including the development of this Proposed Determination analysis, EPA has continued to invest significant resources into understanding developments and emerging trends in battery technologies so that these critically important projections of xEV battery cost may be as reliable as possible.

While other public examples of battery costs to manufacturers remain elusive, several suppliers and manufacturers have made battery-related product announcements since the FRM. Some of these include information suggestive of battery costs or pricing. Some manufacturers have published pricing for battery replacement parts or upgrades available to authorized service providers. Others have offered different options, such as battery size or purchase method, the relative pricing of which may suggest a relationship to battery cost. Finally, stand-alone non-automotive Li-ion battery packs are beginning to become available to end users and their pricing may be informative. While EPA recognizes that the pricing of these early-stage product offerings may be subsidized by their manufacturers for competitive and marketing reasons, these announcements may still be relevant to understanding the evolution of battery pack costs as these products increase their presence in the market.

In 2013-2014, Tesla Motors offered the Model S in two battery pack sizes, 60 kWh and 85 kWh, at retail prices of around $69,900 and $79,900, respectively. Assuming no content difference between the two versions, the retail price differential would suggest a battery cost of $10,000 / 25 kWh = $400/kWh. An alternate analysis presented by Nykvist et al.[396] subtracts the estimated value of added content found in the 85 kWh version (Supercharger, premium tires, and associated markup), resulting in a net price difference of $8,500 or $340 per kWh.

In July 2014, Nissan announced the replacement cost of a 24-kWh battery for the Nissan Leaf at $5499 with core return, which amounts to about $229/kWh net. Although Nissan requires return of the original battery (core), a $1000 credit is then applied for the core, suggesting a full retail price of $6499, or $271/kWh.[397,398,399] Later the same month, Nissan followed up by pointing out that the quoted price is in fact subsidized by Nissan, although they declined to report the amount of subsidy or the actual manufacturing cost.[400] Nissan does not allow purchase of the battery except as a Leaf battery replacement.

In 2015, an independent vendor of OEM parts listed the 2011 Chevy Volt battery pack at $10,208 list price, discounted to $7,228, with no mention of core exchange. Assuming a 16 kWh capacity, these prices would value the battery at $638/kWh and $452/kWh, respectively. Although the product was listed and priced by the vendor, it was on restriction from ordering for reasons that remain unclear.[401,402]

In January 2015, it was reported that the MSRP for a BMW i3 battery pack module was listed at $1,805.89, each module being 2.7 kWh (21.6 kWh total divided by 8 modules). This module price would equate to $669/kWh. A specific dealer was reported to be offering the module at a price of $1715.60, or $635/kWh.[403]

In September 2015, Tesla announced the price for a range-increasing battery pack upgrade for the Tesla Roadster at $29,000, including installation and logistics. Tesla indicated that the quoted price is meant to be equal to Tesla's expected cost in providing the pack, and disclaimed any intention to make a profit. Tesla also indicated that the price per kWh is higher than for a Model S battery due to the low volume production expected for the Roadster upgrade pack (only approximately 2,500 Roadsters were produced). Tesla did not list the kWh capacity of the upgrade pack, but describes it as having approximately 40 percent more energy capacity than the original Roadster pack, which is commonly listed as 56 kWh. This suggests that Tesla's cost for low volume production of this pack is around $29,000/(56*1.4) = $370 per kWh.[404] In October 2015, Tesla further announced that the Roadster upgrade packs would be provided through a partnership with LG Chem.[405] This suggests that the price of the pack may not reflect anticipated savings from the Panasonic-Tesla "Gigafactory" partnership.

In August 2013, the Smart ED was offered with a 17.6 kWh battery, with the option to either purchase the battery with the car, or lease it separately. The vehicle price was $5,010 lower without the battery when the battery was leased at a price of $80/mo. If the $5,010 differential was taken to represent the incremental cost of the battery, it would value the battery at $285/kWh. Of course, the present value of the lease payments would also contribute value to the transaction, and it is possible that marketing considerations could also be represented in the pricing.[406,407,408]

In September 2015, Nissan announced pricing in the UK for the 2016 Nissan Leaf. In a press release from Nissan, equivalent versions of the Leaf having a 30 kWh pack instead of a 24 kWh pack were priced at a difference of 1,600 British pounds. This would amount to approximately 267 British pounds per kWh, or U.S. $411 per kWh (assuming an exchange rate of 1.54 U.S. dollars per pound). It should be noted, however, that although the two versions of the pack appear to be designed to install into the same footprint and volume, any cost comparison is potentially complicated by differences in chemistry and construction of the two versions.[409]

In 2014, Tesla Motors began construction of a so-called "Gigafactory" in Nevada in partnership with Panasonic. This factory is commonly cited by Tesla as enabling a potential 30 percent reduction in battery pack costs from the levels Tesla currently pays. According to one analysis,[410] Tesla's current cost is estimated at about $274 per kWh. A 30 percent reduction on that figure would bring costs to about $192 per kWh.

In April 2015, Tesla announced a home battery pack product called Powerwall, pricing a 7 kWh version at $3,000 ($428/kWh) and a 10 kWh version at $3,500 ($350/kWh). Although designed for stationary home use, the pack design bears similarities to automotive packs, being liquid-cooled and using similar chemistries. The 7 kWh version employs NMC chemistry similar to many production BEVs, while the 10 kWh version employs the NCA chemistry like the Tesla Model S. Tesla also announced a similar product called Powerpack for commercial use. Powerpack was said to be priced at $25,000 for 100 kWh capacity, or $250/kWh. These products are expected to take advantage of much of the cell output of the Gigafactory, suggesting that these products may be priced in anticipation of the cost reductions it is expected to achieve. Table 2.9 summarizes the estimated cost or pricing information derived from the foregoing examples.

Table 2.9 Summary of Published Evidence of Battery Pack Cost and Pricing

		Pack Cost or Price per kWh	
Source of Evidence	Year Applicable	High	Low
Tesla Model S 60 kWh vs 85 kWh comparison	2013-2014	$340	$400
Nissan 24 kWh replacement pricing	2015	$229	$271
Vendor pricing for 2011 Volt pack	2015	$432	$638
Dealer pricing for BMW i3 module	2015	$635	$669
Tesla Roadster upgrade pricing	2015	$370	
Smart ED lease vs buy pricing	2013	$285	
Nissan UK price differential 30 kWh vs 24 kWh	2015	$411	
Tesla Lux Research estimate	2014	$274	
Tesla Lux Research estimate modified by Gigafactory	2017	$192	
Tesla Powerwall	2015-2016	$350	$428
Tesla Powerpack	2015-2016	$250	

It is important to remember that the figures derived from these examples should be interpreted with caution. EPA's cost projections represent direct manufacturing costs and not retail pricing. Also, as previously noted, retail pricing of these early-stage product offerings may be subsidized by their manufacturers and may reflect competitive and marketing considerations that further obscure their true manufacturing cost. Furthermore, some of the estimates are derived from full-product comparisons that may or may not accurately represent the battery portion of the comparison. It should also be noted that the examples presented here represent current pricing, while the EPA analysis applies its BatPaC cost projections to the year 2025.

The Draft TAR noted that the existence of these examples shows that the industry has progressed considerably since the 2012 FRM, when such examples were almost entirely unknown. The identification and packaging of specific battery products for upgrade, replacement or standalone use is a significant development and suggests that the industry is continuing to gain in maturity and is growing along multiple paths. The establishment of MSRPs for many of these products also suggests that manufacturers are beginning to gain confidence in their understanding of the cost structure of battery products. The examples and estimates derived from this analysis, even if approximate, can serve to help ground the various cost estimates and projections that continue to comprise a very active area of research throughout the battery industry, its customer base and other stakeholders.

2.2.4.6 Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEVs) are an emerging form of electrified vehicle having a fully electric powertrain, and are distinguished from BEVs by the use of a fuel cell system rather than grid power as the primary energy source.

FCEVs have only recently entered commercial production, and their market has not yet developed as fully as that of PEVs. Currently, three automakers (Hyundai, Toyota, and Honda) have begun to offer fuel cell vehicles to the mass consumer market or announced specific near-term plans for market launch. Hyundai has offered its Tucson Fuel Cell for lease in select regions of southern California since 2014. Toyota offers its Mirai sedan in at least eight dealerships across both northern and southern California with options for both lease and purchase. Honda has recently released its production Clarity Fuel Cell in 2016. Other automakers are known to be involved in the development of FCEV technology and expected to be moving towards commercial production, but have not yet made public announcements of production models or release dates.

Technology developments relating to FCEVs were reviewed in detail in Draft TAR Section 5.2.4.5. Because EPA did not include FCEVs in its fleet compliance modeling analysis for the Draft TAR nor for this Proposed Determination, please refer to the Draft TAR for additional information on this technology.

2.2.5 Aerodynamics: State of Technology

This section provides an overview of technologies that improve vehicle aerodynamic performance. The focus on vehicle aerodynamics has a long history stemming from the recognition of the relationship between aerodynamic drag and energy consumption. Section 2.2.5.1 outlines the significance of aerodynamic drag and some of the related physical principles and technologies. Section 2.2.5.2, discusses developments in the light-duty vehicle industry to reduce aerodynamic drag, including examples of some recent vehicle introductions. Section 2.2.5.3 focuses on an assessment of the amount of aerodynamic drag improvements that have been implemented by manufacturers in the light-duty fleet as of MY2015. This assessment is in direct response to comments received from the AAM. Section 2.2.5.4 discusses the off-cycle benefits of improved aerodynamic performance. Section 2.2.5.5 discusses the aerodynamics research performed in collaboration with Transport Canada in support of the Draft TAR and this Proposed Determination.

2.2.5.1 Background

Aerodynamic drag accounts for a significant portion of the energy consumed by a vehicle, particularly at higher speeds. Reducing aerodynamic drag can therefore be an effective way to reduce fuel consumption and GHG emissions.

The force imposed by aerodynamic drag results from the flow of air around the vehicle. Aerodynamic performance is thus intimately related to the shape of the vehicle; specifically, it is commonly represented by the product of its cross sectional area as viewed from the front (known as frontal area, or A) and the coefficient of drag (C_d). The product of the two, C_dA, is also known as the drag area of a vehicle. The force imposed by aerodynamic drag increases with the square of vehicle velocity, accounting for its dominance at higher speeds.

The coefficient of drag C_d is a dimensionless value that essentially represents the aerodynamic efficiency of the vehicle shape. The frontal area acts with the coefficient of drag as a sort of scaling factor, representing the relative size of the vehicle shape that the coefficient of drag describes.

C_d and A are determined by the design of the vehicle, and so represent the primary design paths for reduction of aerodynamic drag. The greatest opportunity for improving aerodynamic performance is during a vehicle redesign cycle, when the best opportunity exists to make significant changes to the shape or size of the vehicle.[PP] Incremental improvements may also be achieved mid-cycle as part of a model refresh through the use of revised exterior components and add-on devices. Some examples of these technologies include revised front and rear fascias, modified front air dams and rear valances, addition of rear deck lips and underbody panels, and low-drag exterior mirrors.

Aerodynamic technologies can be divided into passive and active technologies. Passive aerodynamics refers to aerodynamic attributes that are inherent to the shape and size of the vehicle, including any components of a fixed nature. Active aerodynamics refers to technologies that variably deploy in response to driving conditions. These include technologies such as active grille shutters, active air dams and active ride height adjustment.

Significant variations in C_dA can be observed across vehicle classes and among individual vehicles within a class.[411,412,413] Within a class, drag coefficients tend to vary more than frontal areas. Frontal areas are in part a function of interior passenger and cargo space, and therefore tend to track with the interior space expectations associated with a vehicle class. In contrast, drag coefficients are largely a function of body styling and airflow management and may vary significantly with changes in shape and exterior treatment.

As is the case with many technologies that improve vehicle efficiency, manufacturers have a wide selection of technologies for improving aerodynamic performance. These include both passive components, such as body shapes, air dams and underbody panels, and active systems such as grille shutters and adjustable suspensions. In addition, manufacturers have robust development tools based on wind tunnels, clay models, and computational fluid dynamics (CFD) techniques that allow the evaluation of aerodynamic treatments in advance of the creation of physical prototypes. This allows a manufacturer to set aerodynamic targets at the beginning of a vehicle program and simulate multiple alternative vehicle designs to determine which design has the best opportunity to meet the target.

2.2.5.2 Industry Developments

Many vehicle manufacturers have placed emphasis on reducing aerodynamic drag as a means of improving overall vehicle efficiency. While many of the passive and active technologies that EPA identified in the 2012 FRM are not yet found on the entire fleet, the industry is increasingly adopting both types of technologies.

In January 2015, EPA staff attended the 2015 North American International Auto Show (NAIAS) in order to gather information about the state of implementation of various aerodynamic technologies in the vehicles represented at the show. A total of 76 vehicles that appeared to employ aerodynamic devices were viewed, across more than a dozen manufacturers. A memorandum[414] describing this informal survey is available in EPA Docket EPA-HQ-OAR-2015-0827. Although the sample was collected informally and therefore was not random, the information gathered provides some insight into recent industry activity in the application of aerodynamic technology to light-duty vehicles. Table 2.10 shows a breakdown of the aerodynamic devices and technologies that were observed in these vehicles.

[PP] Changes in size are less preferable as a pathway to a reduced C_dA due to the change in utility (e.g., interior space) this may imply.

Table 2.10 Aerodynamic Technologies Observed in Vehicles Investigated at the 2015 NAIAS

Technology		Number of vehicles equipped	Percentage equipped
Active Grill Shutters		14	18%
Underbody Panels	front (full)	28	37%
	front (partial)	22	29%
	middle or side	27	36%
	rear	2	3%
Wheel Dams	Front	56	74%
	Rear	59	78%
Front Bumper Air Dam		18	24%
Total vehicles inspected		76	

This informal survey suggests that manufacturers are implementing both passive aerodynamic devices (panels and dams) and active devices (active grill shutters), as permitted by the various levels of model refresh or vehicle redesign represented in the surveyed vehicles. Further opportunity for more optimized applications of both passive and active aerodynamic technologies is likely to occur as these and other vehicles enter further model refresh or redesign cycles. Besides active grill shutters, other active technologies, such as active ride height or wheel shutters, were not observed in this survey. This could indicate that manufacturers have so far focused on the most cost-effective technologies. Active technologies not yet implemented remain available as additional options for further reducing aerodynamic drag in the future.

Optimizing airflow under the vehicle is an important aspect of improving aerodynamic drag, and is being addressed in a growing number of vehicles by the addition of underbody panels. As indicated by the informal survey, many vehicles already include partial underbody panels covering a portion of the underbody, typically where they would not interfere with mechanical access or exhaust cooling. With careful consideration of access and cooling needs, in many cases, most of the underbody may potentially be streamlined in this way. For example, the Audi R8 includes extensive underbody panels covering almost the entire underbody. [415]

Redesign cycles often present increased opportunities for aerodynamic improvement beyond what is possible in a model refresh. While the 2004 Prius was widely reported as having achieved a very low drag coefficient of 0.26, the 2017 Prius achieves 0.24.[416] Its styling lines, stabilizing fins and underbody panels, supplemented by an active grill shutter, all work together to help reduce aerodynamic drag, providing an example of how whole body analysis can often help maximize the potential for drag reduction even in a vehicle that is already quite aerodynamically efficient.

Another example of optimized application of aerodynamic technology enabled by a redesign cycle can be seen in the 2015 Nissan Murano. Nissan's goal in the Murano effort was to achieve a C_d of 0.31. Its exterior was completely redesigned from its previous 2008-era generation, with the goal of minimizing drag by combining passive aerodynamic devices with an optimized vehicle shape. The development process included 20-percent-scale wind tunnel testing as well as full scale wind tunnel testing and CFD simulations. [417]

The aerodynamic features of the Nissan Murano are listed in Table 2.11. The primary passive devices employed include optimization of the rear end shape to reduce rear end drag, and addition of a large front spoiler to reduce underbody air flow and redirect it toward the roof of the vehicle, thus augmenting the rear end drag improvements. Other passive improvements include plastic fillet moldings at the wheel arches, raising of the rear edge of the hood, shaping of the windshield molding and front pillars, engine under-cover and floor cover, and air deflectors at the rear wheel wells. An active lower grille shutter also redirects air over the body when closed. Together, these measures give the 2015 model a drag coefficient of 0.31, representing a 16 to 17 percent improvement over the 0.37 C_d of the previous model.[417,418]

Table 2.11 Aerodynamic Features of the 2015 Nissan Murano

Design[417]	Detail
Ideal Flow Features	
Minimum airflow into engine compartment	Reduces resistance (just enough to cool)
Airflow under front bumper toward underbody minimized	Reduce as much flow as possible underbody for resistance is caused by the uneven floor
Flow around ends of front bumper toward body sides	Reduce drag, covers front of front tires
Airflow at front wheel arches is routed alongside surfaces of front tires	Reduce resistance that occurs at the front surfaces of the tires
Separation angle at rear of hood is large	Minimize resistance by reducing pressure at low end of windshield, 'hide' windshield wipers and reduce rain droplets in area of air flow
Smooth area at front pillars toward body sides	Vertical vortices are minimized to reduce drag
Optimize of the rear end shape	Assure clean separation of airflow from rear to minimize drag, and equate velocity of airflow from over roof and along body sizes as much as possible to minimize vortices.
Floor -lower bottom edge of front bumper	Reduces airflow toward underbody, route airflow toward vehicle rear in straight path to min flow resistance by uneven floor. Airflow at front of wheelhouses is minimized and wheelhouse design is optimized to direct rearward the air trapped inside - all to reduce resistance at back of the wheel arches.
Computational Fluid Dynamics (CFD) Simulations (80 simulations)	
Active Lower grille shutter at lower opening	Redirects air over the body when closed Higher opening allows sufficient air when grill shutter closed Duct type structure is used to provide direction to the airflow to the heat exchanger and minimize entry into engine compartment elsewhere
Large front spoiler beneath front bumper	Reduces underbody airflow and redirect toward roof of the vehicle Bottom edge is provided with a lip to increase the flow separation angle to further reduce airflow under the body (same as if would further lower the bottom edge of the front spoiler)
Plastic fillet moldings at the wheel arches	To assure air flows along the side surfaces of the front tires (avoid adjusting design of front bumper ends)
Optimize shape of rear edge of hood	To promote separation by increasing flow separation angle, distance windshield wipers from airflow, reduce collection of water droplets
Optimize windshield molding shape	To smooth for wind flow
Outside mirrors optimized for placement	Avoid airflow coming over rear edge of hood and lower edge of front pillar
Optimize shape of vehicle rear end	Shape of rear spoiler, rear combination lamps and rear bumper optimization. Secure larger roof approach resulted in increased pressure recovery and reduced drag by wake flow.
Overall vehicle shape and equal airflow	Balance roof flow and body side flow to reduce vortices
Design optimization to increase airflow to roof	Reduces rear drag caused by wake flow
Rear Spoiler part of roof approach	Tapered toward vehicle rear
Engine under-cover and floor cover	Covers beneath front bumper and over suspension links and muffler piping, raise fuel tank, resulting in smooth underbody flow of air (not full cover)
Reduce airflow into wheelhouses	Large front spoiler extends as far as the front of the wheelhouses and deflectors (optimally shaped) in front of the rear tires, bottom of front spoiler lowered on both sides as capable (governed by ground clearance)
Smoother fenders	Reduce gaps between closure panels
Small vortex-creators	Put vortices in desired places to minimize drag

Despite the extensive use of drag reduction technology on this vehicle, the Murano does not appear to include active ride height technology, which could represent an opportunity to reduce drag even further. While the ride height of an SUV is typically higher than that of a passenger car to provide for off-road capability, this increased ride height can reduce aerodynamic performance. Active ride height technology reduces the ride height at highway speeds, when off-road performance is unlikely to be necessary. These systems may adjust the ride height downward as pre-established speed thresholds or other criteria are met, restoring the original ride height at lower speeds.

An extensive study of advanced drag reduction technologies, including active ride height, has been conducted by Transport Canada and National Research Council Canada.[419] The study suggests that the aerodynamics of even a highly aerodynamic SUV could potentially be improved further by a front and rear ride height reduction of about 40 mm. Several additional active techniques were also explored, including active grill shutters and active extension of the OEM air dam. With grill shutters fully closed, OEM air dam extended 45 percent, and ride height lowered by 40mm in front and rear, estimated C_d was reduced to 0.282 from a baseline of 0.314. Table 2.12 details the effect of other combinations explored in the study.

Table 2.12 Effect of Active Ride Height on SUV Aerodynamic Performance

Technology Package	Baseline C_d (0)	C_d (0 angle)	Difference
Shutters 100% open	0.314		
Baseline (shutters 100% closed, OEM air dam extended 45%, baseline ride height)	0.295 -6%		
Shutters 100% closed, OEM air dam extended 45%, ride height 40mm down front and back		0.282 -4.4% (total 10%)	-0.013
Baseline (shutters 100% closed, OEM air dam extended 30%, baseline ride height)	0.297 -5.4%		
Shutters 100% closed, OEM air dam extended 30%, ride height 40 mm down front and back		0.2802 -5.7% (total 10.8%)	-0.017

In addition to reducing C_d, it is also possible to reduce drag losses by reducing frontal area. While a reduced frontal area would seem to imply a loss of interior volume, the redesigned 2015 Acura TLX sedan shows that with thoughtful design, a reduction in frontal area need not necessarily result in a reduction in interior space. In a 2015 presentation,[420] Acura states that the TLX was redesigned with the help of CFD as well as wind tunnel and real-world coast down testing to achieve a 15 percent lower C_dA compared to the 2012 Acura TL. This was achieved in part by a reduction in frontal area of 1.5 percent (removing 0.5 inches in height and 1 inch in width) that was described as not resulting in a sacrifice in interior space. Further improvements were attributed to a sloped hood and a short rear deck. In addition, welds were eliminated from the forward and rearward edges of the wheel arches by use of a roller hem wheel arch design in place of spot welds, and smoothing transitions between body panels in this area.

The Chevrolet Cruze provides another example of the application of drag-reducing technologies by a major manufacturer in a popular vehicle. The aerodynamic technologies on the 2011 Cruze included active air shutters in the lower grille opening, a front air dam, lower ride height, underbody pans, tire blockers, and rear deck-lid spoiler. GM described these changes as reducing the drag coefficient by more than 10 percent.[421] This program of improvement appears to have continued with the 2016 Cruze,[422] which benefits from what GM describes as: faster windshield rake, faster-sloping rear profile, a rear spoiler, "layered line work" in the hood and body-side panels, headlamp sweep, mounting location of the center-rear stop lamp, and seamless rocker panels. GM describes this vehicle as having a drag coefficient of 0.28.

As another example, the redesigned Ford F150 incorporated a number of aerodynamic improvements over the previous, 2008-era design. However, some trim levels of the 2015 F150 are slightly larger in cross sectional area than the previous model, and as a result some of the aerodynamic benefits may have been lost to this feature. This also indicates that the remaining benefit of these improvements was achieved without loss of interior space. Extensive testing and analysis led to the improved design, including CFD simulations and wind tunnel testing that, according to Ford, allowed aerodynamic performance to be improved while "maintaining the tough truck looks expected from F-150." [423] Some of the technologies on this vehicle include: active grill shutters, underbody covers, canted headlamp and bumper end corners, flush-mounted windshield, a tailgate top that acts as a rear spoiler, a cargo box narrower than the cab (without reducing its volume), angled rear corners, and an air curtain enabled by a duct under the headlamp channels, which minimizes turbulence from airflow around the vehicle.[424,425,426]

Replacement of side view mirrors with side view cameras is another potential drag-reducing technology being considered by OEMs (for example, Tesla and BMW), but has not yet been approved by NHTSA, which sets standards for safety-related equipment including rear- and side-view mirrors. According to the NAS report, side-view mirror replacement with cameras can reduce C_d by as much as 2 to 7 percent. In the interim, one way to reduce mirror drag is to determine optimal placement and optimal design, as noted with respect to the aerodynamic changes to the 2015 Nissan Murano.

2.2.5.3 Feasibility of Aerodynamic Improvements

Public comments on the Draft TAR included several comments regarding the feasibility of aerodynamic improvements as represented by the Aero1 and Aero2 technology cases assessed in the Draft TAR. These cases represent a 10 percent and 20 percent improvement, respectively, in aerodynamic performance from a baseline (2008-era) vehicle.

Some comments expressed concern with the representation of aerodynamic technology that had already been applied by manufacturers to vehicles in the baseline fleet that was created for the Draft TAR analysis. Specifically, there was a concern that every baseline vehicle was considered to have no applied aerodynamic technology, allowing even vehicles that had achieved above average aerodynamic performance to be considered eligible for up to a 20 percent additional improvement. Commenters also suggested that aerodynamic potential should be evaluated on the basis of C_d alone (rather than C_dA, which would imply the possibility of a reduction in interior volume), and that feasible limits on improvement of aerodynamic performance should be recognized and observed.

In the Draft TAR, EPA indicated that it planned to "look at various vehicle categories and examine the … best and worst aerodynamically performing vehicles, using C_dA as a metric," in order to better consider "the remaining potential for aerodynamic improvement within [each] category." EPA has proceeded with this effort by better representing aerodynamic technology present in the baseline. More detail on this update is described in Chapter 2.3.4.4 of this TSD.

In comments on the Draft TAR, Ford commented that the potential for aerodynamic improvement is constrained by other considerations such as consumer desires and needs for utility, space, and styling. While the pursuit of any engineering goal is constrained by competing concerns, EPA continues to believe that manufacturers have a wide variety of technologies from which to draw upon to pursue the reduction of drag losses, as appropriate to the functional characteristics of the vehicle in question. It is not to be presumed that cargo vans, large SUVs or light-duty pickup trucks should be expected to achieve the same potential aerodynamic performance as passenger cars, but within a given segment, paths and opportunities exist to pursue significant improvements as measured relative to less aerodynamically-optimized model generations within the same segment.

2.2.5.4 Results of U.S.-Canada Joint Test Program

In 2013 a Joint Aerodynamics Assessment Program was initiated between Transport Canada (TC), Environment and Climate Change Canada (ECCC), National Research Council (NRC) of Canada, and EPA.[411] This program was conducted in four phases over three years, and examined aerodynamic technologies as currently implemented in a selection of production vehicles, and the effectiveness of potential improvements that were yet to be implemented at the time.

The participating organizations and their respective programs share mutual interests in the primary goals of the program, which are to quantify the aerodynamic drag impacts of various OEM aerodynamic technologies, and to explore the improvement potential of these technologies by expanding the capability and/or improving the design of current state-of-the-art aerodynamic treatments. This program also has provided an important contribution to EPA's technical assessment by offering an opportunity to further validate the feasibility and effectiveness estimates for the passive and active aerodynamic technologies assumed for Aero1 and Aero2.

As discussed in the Draft TAR, the program also provided an opportunity to further validate off-cycle credits that were assigned to active aerodynamics in the 2012 FRM. Two active aerodynamic technologies were identified for pre-defined credit availability of specified amount: Active Grille Shutters and Active Ride Height. See 86.1869-12 (b)(1)(iv). The default value for these credits offered were determined in large part by analysis, using an early version of the EPA ALPHA model to simulate aerodynamic improvements for varying C_d inputs. A key assumption in development of these credits was that active technologies only affect the coefficient of drag, which is assumed to be constant over the speed range of the test. Further validation of this assumption, and of the list of creditable active technologies assumed to be available in production vehicles during the time frame of the rule, was seen as valuable in further supporting the basis of the program. A total of four project phases consisting of twenty-five test vehicles in all EPA vehicle classes was undertaken by the project partners.[412]

Active technologies evaluated by this program include: active grille shutters (opened, closed, intermediate positions, speed effects, yaw effects, leakage effects); a detailed sealing study (i.e. grille shutter sealing; external grille shutter concept); and an active ride height concept (i.e. manual ride height adjustment on vehicles not necessarily equipped to do so from factory). Passive technologies include: Air dams (front bumper and wheels); active front bumper air dams (concept/prototype); underbody smoothing panels (both OEM and idealized prototypes); larger-than-baseline wheel/tire packages; wheel covers (i.e. solid hubcaps); and miscellaneous improvements (including front license plates, decorative grille features and smoothing, tailgates (opened/closed/removed), and tonneau covers). Significantly, NRC facilities include a 9-meter x

9-meter rolling road/moving floor wind tunnel that allows testing of full scale vehicles for accurate comparison of aerodynamic performance with and without active technologies. Listed technologies were not evaluated on every vehicle due to stock configuration, timing and funding.

One valuable outcome of this testing was further validation of the default credit menu values established in the 2012 FRM for active aerodynamic technologies under the off-cycle credit program. Phase 1 of the Joint Program evaluated the aerodynamic performance of eleven (11) vehicles (3 small cars, 5 midsize cars, 2 sport utility vehicles and 1 pickup truck). The conclusions of the Phase 1 study indicated that the active aerodynamic technologies studied are within the range of the default menu credit values anticipated in the TSD of the 2017-2025 GHG rule TSD for active aerodynamic off-cycle credits.

The Phase I study also concluded that the benefit of active grille shutters is constant across the operating speed range, confirming one key assumption in the FRM analysis. In addition, it concluded that passive technologies may each improve the aerodynamics of future vehicles by 1 to 7 percent depending on the passive technology employed and overall vehicle design. This conclusion was based on individual component installation, and does not account for synergistic component effects, nor the effect of integrating passive technologies into an overall vehicle redesign.

Depending on stock vehicle equipment, sometimes it was necessary to fabricate prototype components to make an A to B comparison possible. Prototype components were constructed by study partners Röchling Automotive and Magna International, both of which are Tier 1 suppliers of various aerodynamic technologies to the industry.

Effectiveness values identified in Phase 1 of the Joint Program are shown in Table 2.13.

Table 2.13 Aerodynamic Technology Effectiveness from Phase 1 of Joint Aerodynamics Program

Aero Feature (A-B Testing)		Aero Drag Reduction (%)	Comments
Fixed Air Dam-Bumper		1 - 6%	OEM stock components
Active Air Dam – Bumper (Conceptual)		4 - 9% (fixed air dam + 3%)	Fixed, prototype parts w/ lowest deployment height used
Fixed Air Dam-Wheels		1% (front)/4.5% (front & rear)	
Underbody Panels		1-7% (stock OEM)	Additional 0.5%-4% w/ full body panels. LDT prototype: 8%
Increased Tire Size		-2.0 - 3.2%	17"/18" stock OEM rims vs. 22" optional OEM rims
Wheel Covers		1.5 - 3%	Solid wheel covers only; brake cooling affects not considered
Front License Plates		+/- 0.3%	Negligible impact
Decorative Grille Optimization		1.6%	Smoothing of grille features; function vs. styling trade-offs
Pick-up Tailgates	Open	-5.2%	
	Removed	-7.5%	Open tailgate + 2.3%
Pick-up Tonneau Cover		3.7%	

Phase II of the Joint Program[427] investigated similar technologies using the same methodology of Phase I. Vehicles studied in Phase II included nine vehicles including one small car, one midsize car, one large car, one minivan, and five SUV/crossovers. Active technologies studied included: active grille shutters (including yaw sweep) and active ride height (stock and conceptual). Passive technologies included: underbody panels and air dams, and optional wheel packages. Other technical assessments included turbulent flow impacts and yaw sweep impact. To take into account the fact that vehicles are generally traveling in a windy environment from potentially all wind azimuth angles, the wind averaged drag area was calculated for all cases where a yaw sweep was carried out.

Phase III involved the testing of 4 vehicles: one sedan, one minivan, and two sport utility vehicles.[413] Phase IV involved the retesting of previous vehicles with a focus on turbulent flow, including a small car and a pick-up truck. A report summarizing the results of all four phases is in press at the time of this writing.

One significant outcome of the study was the identification of several high-impact areas for drag reduction. For example, the study found that lowering the ride height while pitching the vehicle nose down could provide significant drag reduction. Also, it was shown that certain combinations of technologies (such as active grille shutters with air dams) often acted with positive synergy (i.e. more than additive) to result in greater reductions in overall drag than the individual technologies alone would suggest.

It should be noted that the Phase I and Phase II studies found that some technologies could potentially increase drag area if poorly applied, and that some individual technologies did not appear to be fully additive when combined with certain others. For example, presence of active air dams was seen in some cases to reduce the effectiveness of adding underbody coverings. Further, combination of active air dams or underbody coverings with active ride height tended to reduce the effectiveness of active ride height. This latter result corroborates with information related to EPA in an OEM meeting that suggested that vehicles that already have underbody coverings are not as highly responsive to adjustments in ride height. On the other hand, combining certain aerodynamic technologies (for example, active grille shutters with air dams) often demonstrated higher total drag reduction than individual additive measurements would have suggested.

Tests conducted during the study often found that lowering ride height while pitching the vehicle at highway speeds (for example, 40mm in the front and 20mm in the rear) provided measurable drag reduction for all vehicles. The highest reduction was observed for vehicle classified as "Large Car". Additionally, underbody panels that are extended to cover the entire surface area underneath the vehicle (full underbody cover) proved to be an efficient way to reduce drag.

It was also found that yaw angle had a significant effect on measurement. Some technologies that perform well at 0° wind angle were found to perform relatively poorly at different wind angles (for example, at 8° to 10°, the differences were quite significant). It was also found that some technologies that tend to work well for one class of vehicle may not perform well for another vehicle class (for example, air dams in turbulent flow conditions were shown to perform better on SUVs than on Large Cars.

In an effort to better represent real-world aerodynamic performance of aerodynamic technologies, the study also investigated the effect of turbulent flow conditions on aerodynamic measurements. The study produced an extensive data set comparing steady smooth and turbulent flow performance for most of the vehicle classes. The study found that both turbulent flow and yaw angle can be important to understanding the effectiveness of aerodynamic technologies in real-world use.

2.2.6 Tires: State of Technology

2.2.6.1 Background

Tire rolling resistance is a road load force that arises primarily from the energy dissipated by elastic deformation of the tires as they roll. Deformation, and hence rolling resistance, for a given tire design is largely a function of vehicle weight and is fairly constant across the normal range of vehicle speeds. Rolling resistance therefore carries an ever-present and often quite significant effect on fuel economy and CO_2 emissions.

Tire design characteristics (for example, materials, construction, and tread design) have a strong influence on the amount and type of deformation and the energy it dissipates. Designers can select these characteristics to minimize rolling resistance. However, these characteristics may also influence other performance attributes such as durability, wet and dry traction, handling, and ride comfort.

Although most tires do not carry markings that indicate their rolling resistance characteristics, indications are that tires with reduced levels of rolling resistance are increasingly being specified by OEMs in new vehicles, and are increasingly becoming available from aftermarket vendors. Lower-rolling resistance tires commonly include attributes such as a higher recommended inflation pressure, optimized materials, optimized tire construction (for lower hysteresis), special geometry (for example, modified aspect ratio or narrower tread width), or stiffer sidewalls for reduced deflection. OEM specification of these tires may be accompanied by changes to vehicle suspension tuning or suspension design to counter any potential impact of the use of these tires on other performance attributes of the vehicle.

2.2.6.2 Industry Developments

As discussed in the Draft TAR, since the 2012 FRM EPA has continued to follow industry developments and trends in application of low rolling resistance technologies to light-duty vehicles, by holding meetings with OEMs and suppliers, attending conferences and trade shows, and regularly monitoring the press and technical literature.

Tires that achieve a 10 percent reduction in rolling resistance (compared to a MY2008-level baseline) are available today, and since the FRM, appear to have continued to comprise an increasing share of tire manufacturers' product lines as the technology has continued to improve and mature. Improvements that would reach up to a 20 percent decrease in rolling resistance relative a 2008 baseline have also seen significant progress in the industry, with indications of increased availability and improved traction and performance characteristics.

Since the 2012 FRM and even before, the tire industry has become increasingly focused on improving tire performance. Recent industry momentum in this direction was captured well in a quote by Kurt Berger of Bridgestone, in a 2014 article in Automotive News.[428] "A low-rolling-resistance tire of 2010 would not be considered a low-rolling-resistance tire today. We've really been pushed in a short time to reduce rolling resistance further." Several typical examples of industry research and implementation efforts are outlined in a 2015 report by Auto World[429]. One example of a specific product embodying lower rolling resistance technology is the Falken

Sincera SN832 Ecorun Tire, with a 22 percent improvement over its immediately previous generation, while maintaining a 27 percent improvement in braking distance. According to a Continental spokesperson cited in the Auto World report, "…improvements of more than 20 percent from one generation to the next [are possible] by introducing rolling resistance optimized tires … an additional 5 percent improvement generation-to-generation is possible." According to Indraneel Bardhan, Managing Partner of EOS Intelligence, so-called "green tires" have achieved a global market share of about 30 percent.

The Automotive News article cited above also discussed ongoing challenges for low rolling resistance tires, including issues such as wet traction, tread wear, and the magnitude of real world benefits in comparison to customer expectations. Customers were said to be relatively indifferent about the fuel economy benefits of low rolling resistance tires, but the perception of differences in handling performance between these tires and traditional tires appeared to be stronger. Due to these perceptions, it was suggested that although original equipment fitments of low rolling resistance tires have been increasing, consumers may tend to replace them with more conventional tires after the original tires wear out, potentially reducing the net fuel-saving impact that would otherwise be expected over the full useful life of the vehicle.

Preliminary results of a study currently underway by Transport Canada (TC) and Natural Resources Canada (NRCan) provides additional support for the view that traction and lower rolling resistance are not necessarily mutually exclusive. In this study, TC and NRCan are coordinating with EPA as they conduct a multi-year testing and evaluation campaign to investigate the rolling resistance and traction characteristics of commercially available tires.[QQ] One aim of the program is to study any correlation that may exist between rolling resistance performance and safety performance (traction) for winter and all-season tires. To date, the campaign has tested 24 winter tires, 50 all season tires, and 5 all-weather tires, testing for energy efficiency, traction performance, and viscoelastic properties of the tread (indicators of rolling resistance and traction performance).

As shown in Figure 2.38, preliminary results of the Transport Canada/Natural Resources Canada study show that winter tires are available with a wide variety of rolling resistance and wet grip characteristics, including tires with both low rolling resistance and good wet grip. For instance, one tire had a rolling resistance coefficient less than 9.0, and a wet grip index greater than 1.1.

[QQ] The primary purpose of this study is to support development of a Canadian consumer information program for replacement tires.

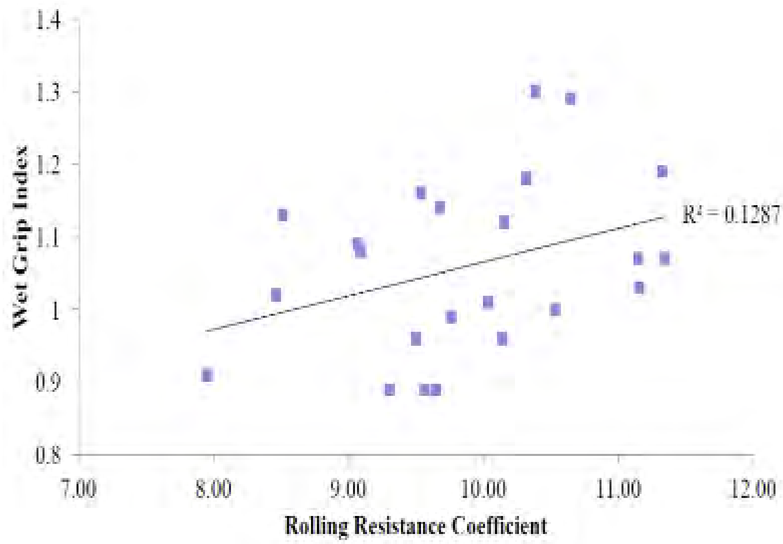


Figure 2.38 Relationship between Wet Grip Index and Rolling Resistance for Winter Tires from Transport Canada/NRCan Study

Countering the common perception that reducing rolling resistance must sacrifice traction performance, the scatter of points in the plot suggests that the range of design variables currently available to tire designers is sufficient to achieve a wide variety of combinations of traction performance and rolling resistance performance, including combinations with low rolling resistance and good traction. Further optimization with respect to cost (which is not represented in the plot) is largely sensitive to manufacturing optimization and production volume, and will play out as demand and production levels for low rolling resistance tires continues to grow.

One example of the potential for careful design to maintain traction in a low rolling resistance tire is seen in the Bridgestone "ologic" design, which appears on the BMW i3 electric vehicle. This tire has a relatively large diameter coupled with a narrow width, reducing rolling resistance by maintaining low deformation through a stiffer belt tension. The larger diameter and unique construction increases the length of the contact patch, which serves to provide improved braking performance and wet and dry traction. An advanced rubber compound and special tread design also contributes.[430] The relatively narrow design is also said to improve aerodynamic performance.[429] The trend toward larger diameter tires with narrower cross-sectional width is also associated with lower tire noise levels, and have been described as one of the likely tire design trends that will continue into the future, particularly for BEVs that value both energy efficiency and quiet performance[429]. As another example, the tire manufacturer Pirelli has ongoing projects focusing on development of new tire polymers through joint ventures with chemical suppliers[429].

Research data presented at the 2014 U.S. DOE Merit Review strongly suggests that significant rolling resistance improvements are accessible to much of the tire market. A project involving Cooper Tires, funded by the U.S. Department of Energy, targets a 30 percent reduction in rolling resistance and a 20 percent reduction in tire weight, while maintaining traction performance.[431] By investigating new materials and methods for reducing rolling resistance in ways that maintain wet traction and tread wear capabilities, this project has suggested that potential improvements in rolling resistance of 10 to 20 percent are achievable by selection of appropriate materials and construction, with examples of reduction in rolling resistance from a prevailing 0.08 to 0.10 down to 0.064 to 0.08.

2.2.7 Mass Reduction: State of Technology

2.2.7.1 Overview of Mass Reduction Technologies

Mass reduction is a key technology for reducing vehicle energy consumption. Vehicle mass has a direct effect on the energy consumed by tire rolling resistance, as well as on the energy needed to accelerate a vehicle, much of which is later lost to friction braking. Through its relationship to acceleration, mass also has implications for the necessary power rating of the propulsion system, with an increased engine size potentially leading to reduced average powertrain efficiency.

Several techniques are available for reduction of vehicle mass, including adoption of lighter-weight materials and part consolidation, among others. Computer-aided engineering (CAE) provides an efficient tool for optimization of vehicle designs along these lines, by allowing rapid modeling and evaluation of potential material substitutions and part modifications.

The cost of reducing vehicle mass is highly variable. Design optimization, consolidation of components, and adoption of secondary mass savings opportunities can result in some cost savings. Secondary mass reduction refers to weight reduction opportunities that become available as the base vehicle becomes lighter. A smaller engine block, transmission and brakes are examples of secondary mass reduction opportunities. Cost increases are often the result of changing from a high density, lower cost material, such as steel, to a lower density, higher cost material, such as high-strength steel, aluminum, magnesium, or composites. The cost for a given mass reduction solution depends on the approach and the material being used. In some cases, cost savings can offset cost increases. Benefits from adopting mass reduction technologies can also include improved performance, such as acceleration, vehicle dynamics, and overall responsiveness.

For the Draft TAR, EPA reevaluated many aspects of mass reduction, including the techniques described above, the cost of mass reduction, the FRM conclusions, and the amount of mass reduction present in the baseline fleet. EPA completed work including research, stakeholder meetings, supplier meetings, technical conferences and literature searches. Public information from these sources were fully described in the Draft TAR, and ultimately formed the basis for the mass reduction cost curves that were developed for the purpose of technology package modeling for that analysis.

EPA has continued monitoring the state of the art of mass reduction, and where applicable, has included updated information on this topic in the present discussion, which builds on the discussion presented in the Draft TAR.

The discussion in this chapter forms the basis for the specific data and assumptions that were used for modeling mass reduction for this assessment, which are described in Section 2.3. This includes the 2015 baseline fleet mass reduction estimates, including mass allowances for safety and footprint changes between the 2008 and 2015 vehicles; a review of the development of the mass reduction cost curves and their application, and mass reduction effectiveness. Further discussion of specific materials (steel, aluminum, magnesium, plastic, glass, and glass fiber and carbon fiber composites), as well as details of their application in regards to issues such as feasibility, cost, safety, and current areas of research, were included in the Appendix to the Draft TAR.

The relationship between mass reduction and safety is an important consideration when considering opportunities for applying this technology. As described in the Draft TAR, NHTSA performed an updated analysis of this issue that was described in Chapter 8 of the Draft TAR.

In recent years, manufacturers have been adopting mass reduction in varying degrees. From vehicles that have adopted large amounts of lower-density materials in their body-in-white (BIW), as with the MY2015 Ford F150 and MY2014 BMWi3, to vehicles that have adopted smaller changes in vehicle design such as an aluminum hood or a steel clamshell control arm in the suspension such as the MY2014 Silverado 1500. The EPA 2015 Trends report illustrates, in Figure 2.39, how in overall sales weighted basis, vehicles have not yet achieved a notable decrease in curb weight, or have continued the trend of using mass reduction to offset increased vehicle content or larger footprint, as the mass difference has remained constant over the past 10 years. The detail within the report notes 2014 results show a 0.5 percent mass increase for cars and 0.7 percent mass decrease for trucks, each on a sales weighted basis.

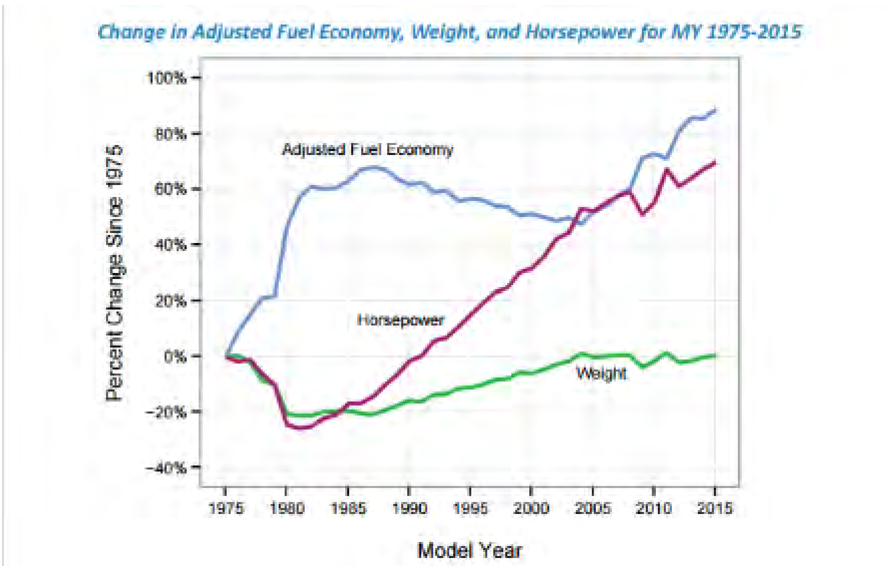


Figure 2.39 Change in Adjusted Fuel Economy, Weight and Horsepower for MY1975-2015[432]

One reason for the current trend of curb weight changes may be the desire to make significant mass-reducing design changes during major vehicle redesigns, hence limiting large mass reductions to new vehicle designs. Recent announcements, as listed in Table 2.14, indicate that the adoption of mass reduction technologies, and resultant lower curb weights, will continue into the future as vehicles are redesigned and as some mass reduction solutions become less costly. One example of significant mass reduction is the 2017 GMC Acadia. GM has stated that the mass of the Acadia has been reduced by 700 pounds through adoption of high-strength steels, a smaller engine option and a smaller footprint.[433] The announcement of the 2017 Chrysler Pacifica in January 2016 also noted 250 pounds of mass reduction through "extensive use of advanced, hot-stamped/high-strength steels, application of structural adhesives where necessary, and an intense focus on mass optimization." Magnesium is also used in the instrument panel and the inner structure of the Pacifica's lift gate, the rest of which is aluminum.[434]

To illustrate the general trend in the use of lightweight materials, Figure 2.40 shows a comparison of metallic material adoption from 2012-2025 included in the 2014 Executive Summary for a study by Ducker Worldwide.[435] The study notes that there was a slight increase in the use of light-weight materials for BIW and closures between 2012 and 2015. The use of AHSS/UHSS grew from 15 percent to 20 percent of the vehicle body and closure parts. Aluminum sheet also grew from 1 percent to 4 percent and aluminum extrusions made it onto the pie chart in 2015. Overall, the analysis expects that steel will remain the dominant material in BIW and closures. According to his, use of plastics is expected to grow to 350kg per average car in 2020, up from 200 kg in 2014, as shown in Figure 2.41. Use of carbon fiber for auto manufacturing is expected to increase from 3,400 metric tons in 2013 to 9,800 metric tons in 2030. According to Ducker Worldwide, the use of magnesium is expected to increase through 2025, as magnesium castings are expected to grow significantly over the next 10 years, further stating, "Growth is highlighted within 'large tonnage' parts like closure inners, IP structures etc. and other body/structural parts."

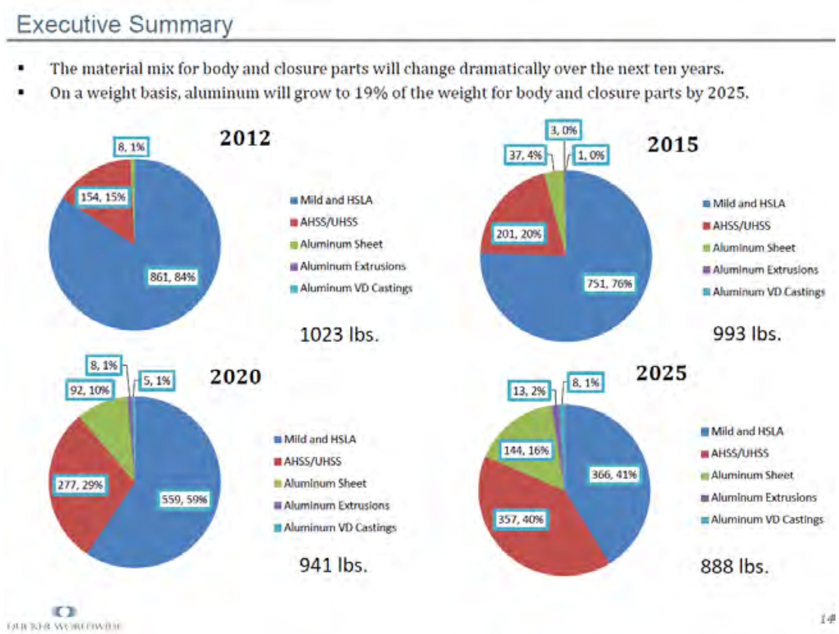


Figure 2.40 Estimated Vehicle Material Change over Time 2012-2025 - Ducker Worldwide[435]

Automotive Market Summary

	2005	2010	2015	2020	2024	Forecasted % CAGR
Vehicle Unit Deliveries	66.5M	77.9M	93.0M	100.7M	109.0M	1.80%
Total Vehicle Wt (MT)	30.2M	35.4M	37.2M	41.1M	44.5M	1.80%
Total FGRP Structures (MT)	79,212	102,371	131,310	167,588	203,704	4.49%
Total CFRP Structures (MT)	3,921	3,771	13,060	37,085	47,011	16.67%
Total CF Demand (MT)	3,666	3,526	10,056	23,456	47,011	13.73%

Figure 2.41 Forecast of Automotive Market Consumption of Composites[436]

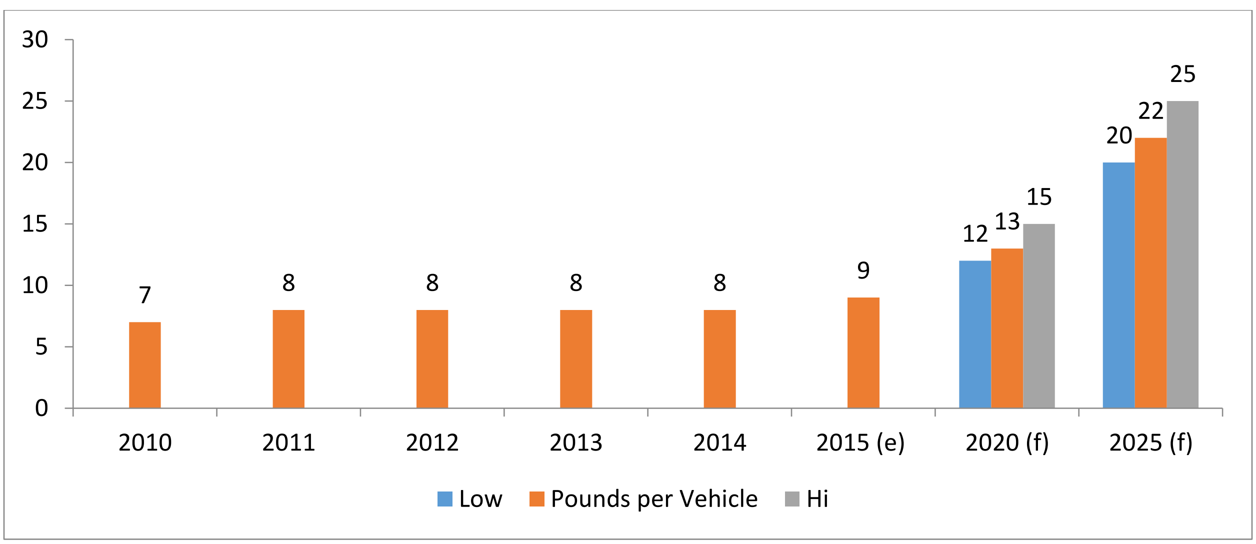


Figure 2.42 Magnesium Growth Expectations through 2025 (Ducker Worldwide)[437]

EPA expects that innovative mass reduction solutions will continue to be developed and adopted through MY2025 and that some mass reduction solutions will be less costly than they are today. Expected advancements include the development of lower-cost high strength steel alloys for body structures (3rd generation steels), lower-cost and higher quality product (for Class A surfaces) from the aluminum Micromill sheet manufacturing processes, and advancements in engineered plastics and composites for structural applications. Developments are also anticipated in design, including further development and use of CAE design tools to characterize new material properties and behaviors. This is expected to result in advances in material use, including optimized load pathway analyses in BIW geometries, and consolidation of multi-part components, resulting in the achievement of mass reduction in the most cost effective way.

2.2.7.2 Mass Reduction Feasibility

Since the FRM, EPA has continuously gathered information on technological advancements and application of mass reduction technologies through a variety of sources, including technical conferences, public reports, material association meetings, academic research, news articles, and stakeholder meetings with manufacturers and suppliers (often including discussion of confidential business information). As previously mentioned, an overview of publicly available information on lightweight materials was included in the Appendix of the Draft TAR. EPA and NHTSA generated two independent holistic lightweighting studies for mass reduction and cost data on light duty pickup trucks (MY2011 and MY2014) and updated existing passenger car (EPA Midsize CUV and NHTSA Passenger car) holistic lightweighting studies completed in 2012. The light duty truck holistic reports join the projects currently described in the FRM on a midsize CUV, one conducted by EPA and one by ARB, and a passenger car, conducted by NHTSA. The Aluminum Association also conducted several projects including a project with EDAG, Inc. to evaluate the EPA Midsize CUV high strength steel BIW CAE model with aluminum material replacement.

DOE also collaborated with Ford and Magna to develop a multi-material lightweight vehicle. This program included a vehicle prototype build and initial durability tests. In addition to vehicle lightweighting, research projects were performed on the mass increases due to safety requirements, for example the IIHS small overlap test (2012). NHTSA conducted a CAE passenger car evaluation and Transport Canada conducted a CAE light duty truck study evaluation which included a crash test of the baseline vehicle. With respect to mass reduction efficiency, the Aluminum Association conducted a study on the impact of mass reduction on fuel economy for various vehicles with Ricardo, Inc. on which the 2015 NAS report comments were based. EPA and NHTSA (through ANL) also re-evaluated the effectiveness of mass reduction on CO_2 and fuel consumption reductions for several vehicle classes, including standard car and light duty truck. The studies on efficiency are addressed in Section 2.3.

In comments on the Draft TAR, Global Automakers and the Alliance of Automobile Manufacturers (AAM) commented that the Draft TAR did not thoroughly discuss some of the real-world constraints on mass reduction. They also commented that the agencies should take into account the time needed to test and qualify new materials before they may be incorporated into vehicles, and the prevalence of global platforms using the same parts in several different vehicle models made in multiple locations. In addition, they recommend that EPA should also consider the need of manufacturers to satisfy customer needs and expectations and regulatory requirements. In addition, Global Automakers stated that many mass reduction technologies have unintended consequences that customers will not accept. For example, they contend that light-weighting technologies can increase noise, vibration and harshness (NVH) to levels unacceptable to consumers.

EPA recognizes that there are many factors which contribute to the implementation of mass reduction technologies by vehicle manufacturers. These potential barriers to mass reduction are different from manufacturer to manufacturer and are related to level of experience with the technology, supplier experience, vehicle functional objectives, and global and platform manufacturing constraints. In each of the mass reduction studies used to inform the Draft TAR and the Proposed Determination analyses, many alternatives are presented for reducing mass. Because the studies were done holistically, mass reduction solutions were identified across the entire vehicle and the studies considered technologies from a wide variety of sources. In addition, the results of the Proposed Determination analysis do not project a large amount of mass reduction, on average, across the light-duty fleet. As such, manufacturers will most likely have many choices as to which mass reduction solutions to choose which meet the requirements for OEM and supplier experience, global manufacturing and vehicle functional objectives.

AAM also commented on some of the challenges associated with mass reduction, specifically on material availability. The September 2016 study by the Center for Automotive Research (CAR)[438] contains (page 11) a list of challenges for various lightweight materials (HSS, Aluminum, Magnesium, Composites). In addition, in order to achieve the higher levels of percent mass reduction, the study maintains that magnesium and composites would be required. EPA agrees that magnesium, aluminum and composites are important materials for mass reduction and are already being applied on many current production vehicles to reduce mass.

Regarding composites, one of the primary concerns has been CAE simulation for various material compositions, availability of low cost carbon fiber to use in the composite material, and a recyclable resin material. Modeling composite behavior can and has been done: for example, BMW has produced the BMWi3 which has a composite/aluminum BIW. BMW is also supporting work at the University of Delaware to develop a B-pillar made of composite material and the results have been presented at the SAE Government/Industry meeting in 2015 and presentation of component build and test in 2016.

With respect to aluminum, the September 2016 CAR report[438] states there are concerns with conversion of the steel-based supply-chain infrastructure, paint shop issues (thermal expansion, aluminum surface characteristics), robustness of the supply base, and the need for redesign of body shop assembly technology. The aluminum industry is poised to supply aluminum needs and the Micromill technology can be used to supply some of that demand as is being done on the F150.[439] EPA agrees that aluminum stamping is different from steel stamping, but as demonstrated by the F150 program, it is feasible in a high volume production environment. In regards to thermal expansion, OEMs are able to manage the thermal properties of various materials, including aluminum, as demonstrated by the many current production vehicles that have aluminum hoods and other closures. Further, GM has developed a way to join aluminum vehicle components as an alternative to the vehicle manufacturing techniques used by Ford on the F150.[440]

The following section provides a description of the multi-material approach to lightweighting being used by OEMs, and presents some examples of current vehicle designs that have adopted notable mass reduction which resulted in significant curb weight reductions. Further sections present an overview of the various holistic mass reduction and cost studies that were completed since the FRM. The studies provide technology, primary and secondary mass reduction, and cost information that was used to create cost curves for application of mass reduction technology for a passenger car and light duty pickup truck, which were used in the Draft TAR analysis and remain largely unchanged for the Proposed Determination analysis.

2.2.7.3 Market Implementation of Mass Reduction

A trend of slight reductions in curb weight in the new vehicle fleet has been observed in both the MY2014 baseline used in the Draft TAR analysis and the MY2015 baseline used in this Proposed Determination analysis. Data reported in the 2016 EPA Trends report indicates that the overall sales-weighted curb weight has remained steady over the past 10 years. In MY2008, the sales weighted vehicle weight was 4,085 pounds with a footprint of 48.9 square feet, but by MY2015 it was 4,035 pounds and 49.4 square feet, a decrease of 50 pounds and an increase of 0.5 square feet. [441] During this period, additional equipment to meet safety regulations led to addition of mass, which would be included in the MY2015 weights.

Table 2.14 lists a number of vehicle lightweighting efforts that have been introduced into the market over the past few years. Some vehicles adopted high strength steel solutions, up to 2 GPa tensile strength steels, in their BIW such as in the Audi Q7, Acura TLX, Nissan Murano and Cadillac CTS redesigns. The MY2015 F150 and the MY2014 Range Rover by Land Rover have both adopted a number of lightweighting components including aluminum body and cabin structure, aluminum closures, etc.

Table 2.14 Examples of Mass Reduction in Selected Recent Redesigns (Compared to MY2008 Design)[RR]

Vehicle Make	2008 Model Year curb Weight (kg)	Model Year	Change in Vehicle Curb Weight (kg)	% Change	% Footprint Change
Acura MDX	2070	2014	238	11.5%	+0.5%
Audi Q7	2320	2014	325	14%	0
Land Rover Range Rover	2400	2014	336	14%	+5.2%
Silverado 1500 Crew Cab 4x4	2422	2014	86	3.6%	n/a
Ford F150 2.7L EcoBoost, 4x2 Supercrew	2446	2015	318	13%	n/a
Nissan Murano	1500	2015	30	2%	n/a
Cadillac CTS	1833	2015	110	6%	+1.6%
Honda Pilot	4367	2016	131	3%	+6.1%
Chevy Cruze[442]	1425	2016	114	8%	n/a
Chevy Malibu[443]	1552	2016	136	9.2%	+0.3%
GMC Acadia	2120	2017	318	15%	-7.8%
Chrysler Pacifica	2110	2017	114	5.4%	+8.2%
Cadillac XT5[444]	1893	2017	82	4.5%	+2.7%

The following excerpt from an Audi[445] press release represents the holistic engineering approach that achieved significant levels of cost effective mass reduction:

[RR] Some vehicles were redesigned twice since 2008 and so the changes are not exactly the same as noted in the articles from which some of the information was taken, because the table references differences between 2008 and 2014.

> "Although it [the Audi Q7] is shorter and narrower than its predecessor, the cabin is longer and offers more head room. 20 years of experience with lightweight construction flow into the new Audi Q7. Equipped with the 3.0 TDI engine, the new Audi Q7 tips the scales at just 1,995 kilograms (4,398 lb.), which is 325 kilograms (716.5 lb.) less weight … the Q7 with the 3.0 TFSI engine is even lighter, weighing just 1,970 kilograms (4,343.1 lb.). Lightweight construction has been applied in all areas, from the electrical system to the luggage compartment floor. The key is the body structure, where a new multi-material design reduces its weight by 71 kilograms (156.5 lb) … ultra-high-strength parts made of hot-shaped steel form the backbone of the occupant cell. Aluminum castings, extruded sections and panels are used in the front and rear ends as well as the superstructure. They account for 41 percent of the body structure. Other parts made entirely of aluminum are the doors, which shave 24 kilograms (52.9 lb.) of weight, the front fenders, the engine hood and the rear hatch. Audi uses new manufacturing methods for the production and assembly of the parts. The crash safety and occupant protection of the new Audi Q7 are also on the highest level."

The holistic design approach enables secondary mass savings that can be achieved due to reduced load requirements as the overall vehicle becomes lighter. One example of secondary mass reduction is the potential adoption of a smaller engine in a light weighted vehicle. Ford mentioned in a 2010 International Magnesium Association article that:

> "Strategic use of lightweight and down-gauged material allows a vehicle's powertrain to be smaller and more fuel-efficient. Combining magnesium with aluminum for the MKT lift gate's panels instead of steel saves 22 pounds in vehicle weight. When coupled with other weight-saving measures, re-matching the vehicle with a smaller powertrain – known as right-sizing of power to weight -- is a key factor in achieving greater fuel economy."[446]

2.2.7.4 Holistic Vehicle Mass Reduction and Cost Studies

As shown in the Draft TAR, the 2017-2025 FRM Joint Technical Support Document (2012 TSD) contained a linear mass reduction cost curve for direct manufacturing costs (DMC) in the expression of DMC ($/lb.)=$4.36(percent-lb.) x Percentage of Mass Reduction level (percent) as shown in Figure 2.43. This equation starts at $0/kg for no mass reduction and increased at a constant rate of $4.36/(percent-lb.) for each percent mass reduction (ex: $0.44/lb. for 10 percent MR on a 4,000 lb. vehicle and $0.66/lb. for 15 percent on same) and was applied to all 2008/2010 MY vehicles in which no mass reduction was assumed. This cost curve expression was based on a number of available data sources on mass reduction which included a number of papers on individual components.

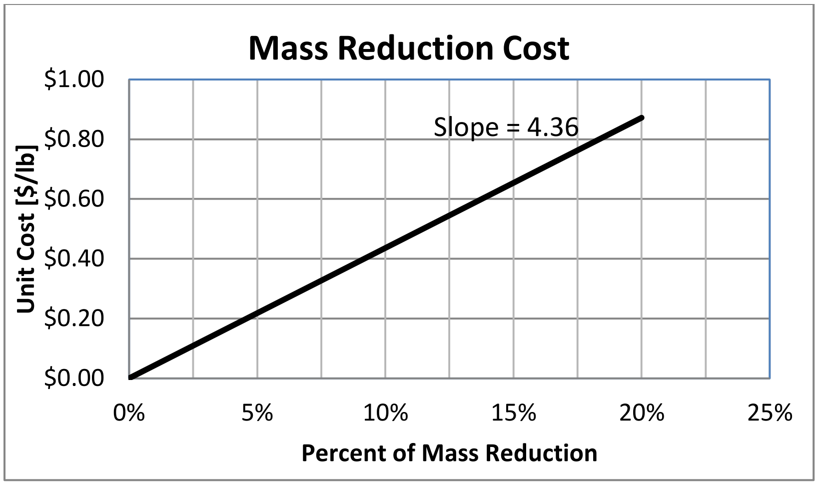


Figure 2.43 Mass Reduction Cost Curve ($/lb.) for 2017-2025 LD GHG Joint Technical Support Document

In order to capture a more complete picture of the potential for mass reduction and related costs, EPA, NHTSA, ARB, and DOE committed significant resources to acquire mass and cost information through a number of holistic vehicle studies as listed in Table 2.15. The projects were performed with constant performance as a goal, and hence the benefits of all mass reduction solutions were applied to improve fuel efficiency and lower CO_2 emissions. Each project includes many steps including baseline vehicle teardown, component/system examination for mass reduction technologies, direct manufacturer cost estimation for mass reduction technologies and related tooling, CAE safety crash evaluation, NVH assessment and durability analyses. The mass reduction technologies included in these studies were found in a variety of sources including those found on other vehicles, technologies in development at suppliers and material companies, technologies developed in other government funded projects, etc. Cost estimates were made by the project contractors based on their extensive automotive experience and industry contacts.

The DOE/Ford/Magna joint project itself did not include a cost study for its two evaluations - Mach 1 (25 percent MR) and Mach 2 (50 percent MR). However, DOE did fund two independent cost studies related to this work. One study was for a 40 to 45 percent mass reduction vehicle which identified the necessary cost of carbon fiber in order to make the design solution a reality. These results were presented at the DOE Annual Merit Review (AMR) in 2015. A second independent study was also funded by DOE in 2016 and presented at the 2016 DOE AMR. This study focused on an assessment of the multiple strategies addressed in the earlier phase in terms of weight reduction, cost premiums, and risk factors in order to establish a prioritized spectrum of lightweighting opportunities. The work then applied process Technical Cost Models (TCMs) to priority lightweight material manufacturing technologies to evaluate cost structures and understand the relative leverage of key cost drivers.

The Mach 1 work also included several additions which included the buildup of seven lightweight vehicles for a number of durability and crash analyses as well as testing of some of the project's new technologies. Two other studies provided insights into the mass add for meeting the IIHS small overlap test which is required in order to achieve the IIHS rating of Top Safety Pick. NHTSA funded a follow-up study on their 2012 passenger car work and Transport Canada funded a follow-up study on the EPA 2015 light duty pickup truck. The studies provided a revised final cost and mass reduction to the original works. EPA also greatly appreciate and acknowledge the work of many individual companies, academia representatives, and material associations to provide information on lightweighting technologies, both in production and in research, to the agency contractors for the holistic vehicle studies. This information was also used as the basis for material information contained in the Appendices to the Draft TAR to address topics of feasibility, mass reduction, cost, safety, research and recycling.

Table 2.15 Agency-Sponsored Mass Reduction Project List since 2012 FRM

	Agency	Description	Completion Date	Reference
Pass Car/ CUV Studies	US EPA	Phase 2 Midsize CUV (2010 Toyota Venza) Low Development (HSS/Al focus)	2012	Final Report, Peer Review and SAE Paper EPA-420-R-12-019, EPA-420-R-12-026, SAE Paper 2013-01-0656
	ARB	Phase 2 Midsize CUV (2010 Toyota Venza) High Development All Aluminum	2012	Final Report and Peer Review http://www.arb.ca.gov/msprog/levprog/leviii/final_arb_phase2_report-compressed.pdf http://www.arb.ca.gov/msprog/levprog/leviii/carb_version_lotus_project_peer_review.pdf
	NHTSA	Passenger Car (2011 Honda Accord)	2012	Final Report, Peer Review, OEM response, Revised Report ftp://ftp.nhtsa.dot.gov/CAFE/2017-25_Final/811666.pdf http://www.nhtsa.gov/Laws+&+Regulations/CAFE+-+Fuel+Economy/ci.NHTSA+Vehicle+Mass-Size-Safety+Workshop.print http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf
	DOE/ Ford/ Magna	-Passenger Car (2013 Ford Fusion) Mach 1 and Mach 2 projects -Cost Study for 40-45% Mass Reduction -Mass Reduction Spectrum Analysis And Process Cost Modeling Project	2015	http://energy.gov/sites/prod/files/2015/06/f24/lm072_skszek_2015_o.pdf http://energy.gov/sites/prod/files/2014/07/f17/lm072_skszek_2014_o.pdf http://energy.gov/sites/prod/files/2014/07/f17/lm088_skszek_2014_o.pdf http://avt.inl.gov/pdf/TechnicalCostModel40and45PercentWeightSavings.pdf http://energy.gov/sites/prod/files/2016/06/f33/lm090_mascarin_2016_o_web.pdf SAE papers include:2015-01-0405~0409,2015-01-1236~1240,2015-01-1613~1616
	NHTSA	Passenger Car small overlap mass add	2016	Final Report http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf
Light Duty Truck Studies	EPA	2011 Silverado 1500	2015	Final Report, Peer Review and SAE Paper EPA-420-R-15-006,SAE Paper 2015-01-0559
	NHTSA	2014 Silverado 1500	2016	Final Report November 2016
	Transport Canada	IIHS small overlap mass add on LDT (EPA)	2015	Final Report and Peer Review https://www.tc.gc.ca/eng/programs/environment-etv-summary-eng-2982.html Peer Review (EPA docket)447

The holistic vehicle studies in Table 2.15 are nearly all focused on MY2008/2010 designs. This was important for two reasons. The first is that the 2012 FRM analysis was based on the ability to reduce the mass of the MY2008 fleet. Second, these mass reduction studies provided insight into many mass reduction solutions that had not yet been widely adopted by manufacturers. The MY2014 new-generation light duty pickup truck evaluated by NHTSA was a 'next step' approach to evaluate the mass reduction potential and cost of converting from a more high strength steel approach (compared to the 2008 design) to other lightweight materials including aluminum and CFRP. It should be noted that the cost curve expression used by EPA in the Draft TAR and this Proposed Determination differs from that used by NHTSA in the Draft TAR CAFE assessment .

EPA is using the information from the publicly available government sponsored studies in its modeling of mass reduction and related costs for all the vehicles sold in the US. The vehicles for the holistic vehicle projects were chosen based on their representation of high sales volume vehicles, as the Honda Accord and Chevy Silverado 1500, and/or representative of new vehicle designs that were showing increasing popularity, as the Toyota Venza. The projects were conducted over the past 6 years and were multi-million dollar efforts. The same detailed information collected in these projects were not readily available from any other source - especially cost information and secondary mass effects. Additional mass comparison information was found to be available through the A2Mac1 vehicle databases and that information has been used to supplement our analyses on mass differences - especially on mass add for vehicle footprint increases. Ducker Worldwide executive summaries have also provided insights into aluminum and steel material trends.

To understand how the results from our projects relate to real world lightweighting efforts, EPA has met with OEMs and attended many technical conferences over the past four years. It was observed that there are cost savings to be achieved from lightweighting MY2008/2010 design vehicles and more is expected as costs are reduced through material recycling and optimization of material use. EPA agrees that some mass reduction technologies will add cost, however recent developments in material processing, as with development of 3rd generation steels[SS] and Alcoa's Micromill for aluminum, indicate that these costs may be less than that utilized in the studies. In addition, the decrease in metal material pricing over the past year has not been included in most of the holistic vehicle studies. EPA understands that OEMs have typically utilized mass reduction technologies to offset the weight of added features or safety measures.

In their comments on the Draft TAR, AAM commented that the mass reduction studies used to develop the cost curves were "overly optimistic" due to the vintage of the vehicles studied (Venza and Silverado) and scope of the studies (Venza). (AAM also noted that they did not have cost curves to present as an alternative.) EPA disagrees that the cost curves used in the Draft TAR analysis are inappropriate and has continued to apply these cost estimates in the Proposed Determination. Within any given model year, the fleet will be comprised of vehicles with a variety of design vintages, and designs with varying degrees of mass reduction implementation. In recognition of these variations, EPA adopted an approach in the Draft TAR to determine the initial starting point on the cost curve that is appropriate for each individual model in the baseline. When applying the cost curves based on studies with earlier vintage vehicles (i.e. the 2009 Venza, 2011 Accord, and 2011 Silverado) and the more recent 2014 Silverado, EPA aligned the curves so that they would maintain a consistent "null" technology reference point at 0 percent mass reduction. EPA believes that the critical point, consistent with the comment from

[SS] Nanosteel mentioned in their comments to the Draft TAR that our costs were overestimated for 3rd generation steel.

AAM, is that vehicles in the baseline are placed at the appropriate location on the cost curve. As mass reduction technologies are continuously introduced into the fleet from year-to-year, analyses based on progressively updated baseline years would involve placing vehicles further along the cost curve. Using this approach, differences in the vintages of the vehicles used to create the cost curves will not have a primary influence on the incremental costs applied for mass reduction.

2.2.7.4.1 EPA Holistic Vehicle Mass Reduction/Cost Studies

EPA funded two holistic vehicle mass reduction/cost studies for the Midterm Evaluation between 2010 and 2015. The first study was the Phase 2 low development (steel BIW) lightweighting study on a Midsize CUV performed by EPA with FEV North America, Inc., EDAG, Inc. and Munro and Associates, Inc. and was focused on achieving 20 percent mass reduction which resulted in a high strength steel structure with aluminum closures amongst other technologies. This was a follow up to the Phase 1 paper study on the Midsize CUV performed by Lotus Engineering and includes in-depth analyses on cost and CAE safety analyses of the vehicle. The second study was a lightweighting study on a 2011MY light duty pickup truck and was performed by the same contractors using a similar methodology however added in the dynamic vehicle analyses and a number of component evaluations performed with CAE. The result was an aluminum intensive vehicle with high strength steel/aluminum ladder frame.

EPA's cost curve development methodology for both projects is based on a cumulative additive approach of the best-rated technologies in terms of $/kg. Primary mass reduction technologies (technologies not dependent on mass savings in other areas of the vehicle) are listed along with the related costs and mass savings. The $/kg for each technology is calculated and then the order of the technologies is sorted from lowest $/kg to highest. The original mass and costs are then each added in a cumulative manner and then the resultant $/kg is calculated at each technology and a related percent mass reduction. Secondary mass savings, those mass savings which are dependent on other mass savings within the vehicle, are noted on a component evaluation basis, summed, and then applied at the solution point for the project. Since the secondary mass savings are based on the size of the component - hence material basis - then this can be proportioned across the whole range of primary mass reduction curve. The cost savings are also proportioned. Two assumptions work into this costs curve methodology: 1) OEMs will adopt the lowest cost mass reduction technologies first; and 2) secondary mass savings, such as a resized engine and/or chassis systems, can occur at all percent mass reduction points. This methodology works into EPA's mass reduction modeling methodology for the Proposed Determination.

Other related studies to the Phase 2 Low Development Midsize CUV include the Phase 2 High Development study funded by ARB. ARB hired Lotus Engineering to compete an in-depth look into the aluminum intensive (High Development) Midsize CUV and included CAE safety analyses and an in-depth cost analyses. Both of the Phase 2 studies, High Development and Low Development, are follow-up studies to the Phase 1 paper study by Lotus Engineering on the Midsize CUV. Following the Phase 2 studies, the Aluminum Association Automotive Technology Group contracted with EDAG, Inc. to evaluate aluminum material replacement within EPA's CAE model of the Midsize CUV BIW. A cost analyses was also performed by EDAG for this project.

2.2.7.4.1.1 Phase 2 Low Development Midsize CUV Updated Study and Supplement

The Phase 2 Low Development (steel BIW) Midsize CUV lightweighting study was completed in August of 2012. The results of this work were peer reviewed through an independent contractor as well as through the SAE paper publication process. Feedback was received by OEMs and others independent of the official peer review process.

The MY2010 Toyota Venza was chosen as the base vehicle for this work and vehicle teardown and coupon testing revealed that the base vehicle BIW included high strength steel components made of HSLA 350, HSLA 490, DP500, a 7000 aluminum rear bumper and HF1050 B pillar and side roof rail. After consideration of nearly 150 lightweighting ideas, the project's final lightweighting results stated that 18.5 percent mass reduction was achieved for a cost savings of $0.47/kg. The report also stated that if aluminum doors were included then the mass save would be 20.2 percent with a cost savings of $0.11/kg. To make the non-compounded cost curve, the primary lightweighting ideas were listed with the lowest $/kg to the highest $/kg which reflects an approach where the OEMs would choose the less expensive, or cost saving, technologies first. Then the mass and cost data were individually cumulatively added and a cumulative $/kg was determined at each technology addition to create the non-compounded curve. The compounded curve was developed by determining the secondary mass savings at the primary solution point and then the mass savings were ratioed across the primary cost curve to yield the final cost curve with compounding. A short summary of this work and the cost curve(Figure 2.44) were included in the 2012 FRM analysis.

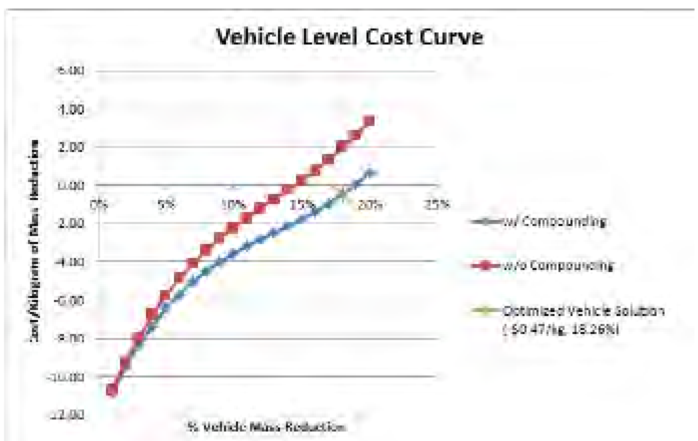


Figure 2.44 Original Phase 2 Low Development Midsize CUV Lightweighting Cost Curve[448]

Additional consideration was given to the feedback EPA and FEV received on the study as well as to methodology updates which were made during the MY2011 light duty truck lightweighting study after the FRM. Modifications made to the data for the original curve, shown in Figure 2.44, included adding in the aluminum doors as a lightweight technology, and removing several features including the magnesium engine block and the cost savings for some of the light weighted plastic components. Several customer features were put back into the vehicle including the lumbar and active head rest for the back seat and the cargo cover. A mass and cost allowance for NVH was added as well as the related cost savings for the secondary mass which had not been accounted for in the FRM methodology. The revised cost curve is shown in Figure 2.45 and is 17.6 percent mass reduction at +$0.50/kg. Also included are the $/kg and percent mass reduction solution points for two aluminum BIW Midsize CUV studies. First is the work funded by ARB from Lotus Engineering on the Phase 2 High Development

Midsize CUV aluminum intensive project which utilized an aluminum BIW design and results came in at -$0.64/kg for 31 percent MR,[452] per our calculations of study results. Second is the aluminum intensive point from the Aluminum Association work of 27.81 percent mass reduction at $1.12/kg, in which EDAG utilized the same CAE baseline model developed for the EPA Phase 2 Low Development Midsize CUV work.[454]

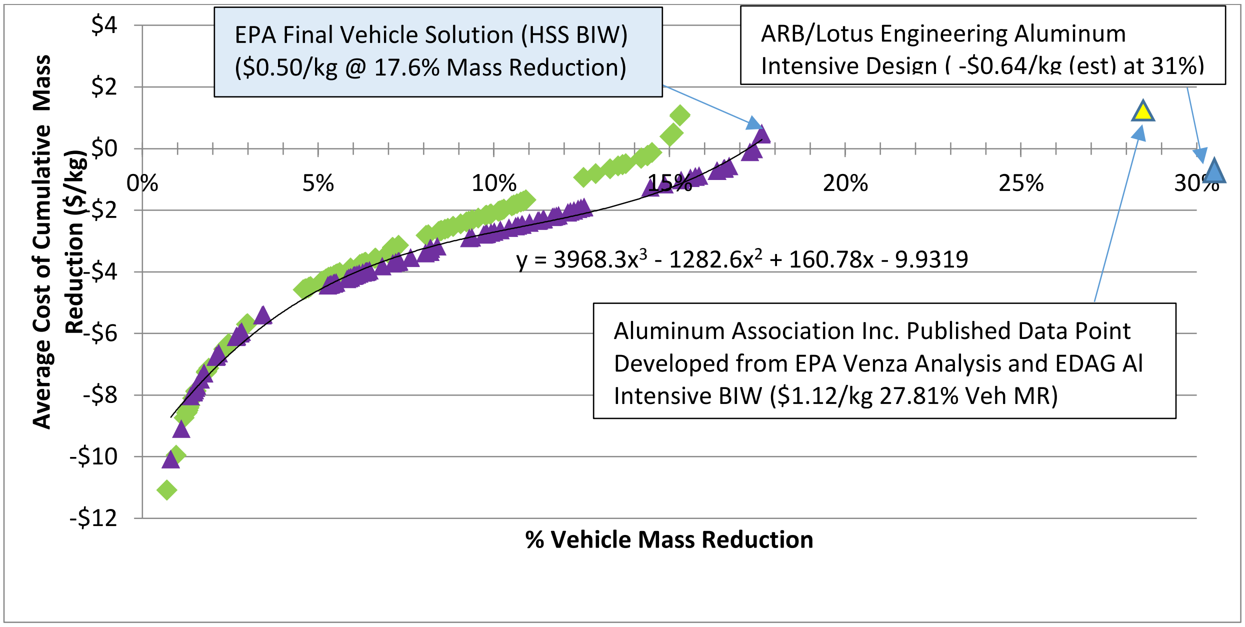


Figure 2.45 Revised Cost Curve for the Midsize CUV Light Weighted Vehicle

This cost curve, in Figure 2.45, is clearly different from the 2012 FRM cost curve for mass reduction, in Figure 2.43, in which all mass reduction points were associated with positive costs. The EPA Phase 2 Low Development Midsize CUV holistic vehicle study is a whole vehicle study which examines nearly every component in the vehicle for mass reduction potential and calculates a related cost and mass save for each and reviews them from most cost/kg saved to most costly cost/kg. This methodology was chosen based on the understanding that OEMs will choose the cost saving technologies first and that some cost mass reduction technologies will be paid for by the cost save mass reduction technologies. A vehicle cost curve similar to the FRM expression could be achieved if cost technologies were listed first in the cumulative adding approach and hence losing the appearance of the cost saving technology ideas. However, this is not the approach that OEMs are utilizing for lightweighting. For example, a 2016 publication by CAR contains an illustration and caption which states that "(Figure 2.46) illustrates a generic cost curve for lightweighting that is broadly supported."[450] GM has also claimed publicly to its potential investors that over $2B[449] was saved in material costs, which suggests that costs can be saved with mass reduction over several passenger vehicles. It is very likely that some of this savings was due to the decreased material costs over the past year in addition to the cost-saving lightweighting approaches.

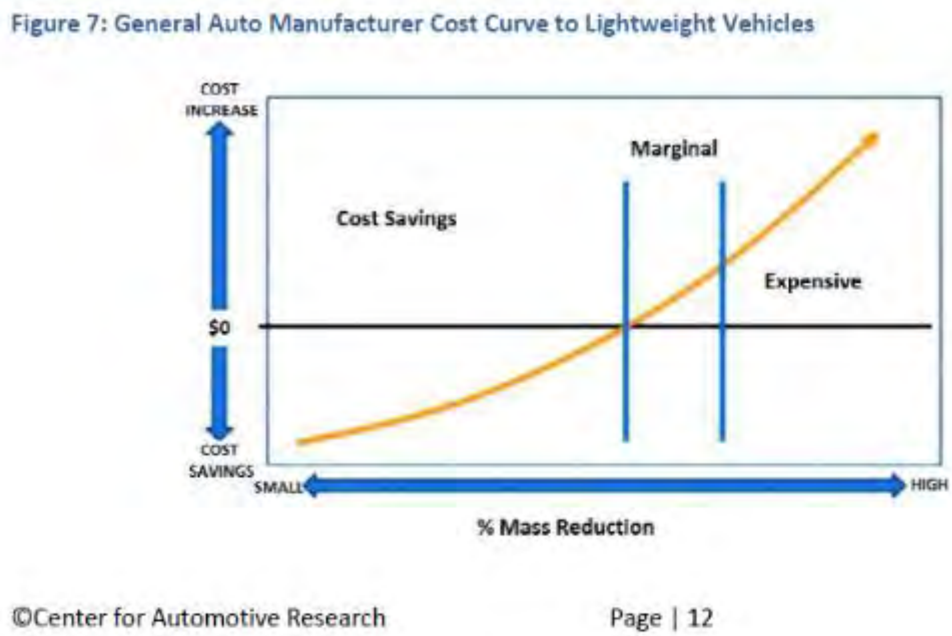


Figure 2.46 Cost Curve Figure from CAR: "A Cost Curve for Lightweighting That Is Broadly Supported"[450]

2.2.7.4.1.2 Light Duty Pickup Truck Light-Weighting Study

The U.S. EPA NVFEL contracted with FEV North America to perform this study utilizing the methodology developed in the Midsize CUV lightweighting effort (2012) and the study was completed in 2015. The results of this work went through a detailed and independent peer reviewed as well as through the SAE paper publication process. Feedback was received by OEMs and others independent of the official peer review process.

For this study a 2011 Silverado 1500 was purchased and torn down. The components were placed into 19 different systems. The components were evaluated for mass reduction potential given research into alternative materials and designs. The alternatives were evaluated for the best cost and mass reduction and then compared to each other. CAE analyses for NVH and safety was completed for the baseline and the light-weighted aluminum intensive vehicle. A high strength steel structure with aluminum closures was the first choice of a solution for this project; however, this was not fully completed for the decision was made by the project team to change course and pursue the aluminum structure solution due to the expected introduction of the aluminum intensive F150 into the marketplace. Durability analyses on both the baseline and light-weighted vehicle designs were performed through data gathered by instrumenting a Silverado 1500 light duty pickup truck and operating it over various road conditions. Included in the durability analyses are durability evaluations on the light weighted vehicle frame, door and other components in CAE space. The crash and durability CAE analyses allowed for gauge and grade determinations for specific vehicle components. Load path redesign of the light duty truck structure (cabin and box structure and vehicle frame) was not a part of this project.

As shown in Figure 2.47, the most mass reduction was achieved in the Body System Group - A- (Body Sheet metal) in which the cabin and box structure and the closures, etc. were converted to aluminum. The suspension system is the second highest system for mass reduction and includes composite fiber leaf springs. Mass reduction technologies with cost save examples include 1) material and design optimization in the connecting rods, 2) material and design through use of vespel thrust washer versus roller bearings, 3) material processing in the Polyone and Mucell applications, 4) material substitution in the thermoplastic vulcanizates (TPV) vs. EPDM static and dynamic weather seals, 5) material and part consolidation in the passenger side airbag housings, and 6) design and processing through incorporation of the half shafts and the Vari-lite® tube process by U.S. Manufacturing Corporation. A complete listing of vehicle technologies can be found in the online report[451] and Figure 2.47 shows that there was a 50kg and $150 allowance for NVH considerations.

			Mass Reduction Impact by Vehicle System (Includes Secondary Mass Savings)						
Item	System ID	Description	Base Mass "kg"	Mass Reduction "kg" (1)	Cost Impact NIDMC "$" (2)	Cost/ Kilogram NIDMC "$/kg" (2)	Cost/ Kilogram NIDMC + Tooling "$/kg" (2)	System Mass Reduction "%"	Vehicle Mass Reduction "%"
		1500 Series Chevrolet Silverado Pick-Up Truck							
1	01	Engine System	239.9	31.8	-92.83	-2.92	-2.63	13.3%	1.3%
2	02	Transmission System	145.3	39.4	-96.57	-2.45	-2.47	27.1%	1.6%
3	03A	Body System Group -A- (Body Sheetmetal)	574.7	207.1	-1194.86	-5.77	-5.77	36.0%	8.4%
4	03B	Body System Group -B- (Body Interior)	247.0	34.0	-127.23	-3.74	-3.78	13.8%	1.4%
5	03C	Body System Group -C- (Body Exterior Trim)	40.5	2.1	2.73	1.28	1.28	5.3%	0.1%
6	03D	Body System Group -D- (Glazing & Body Mechatronics)	50.9	4.5	2.30	0.51	0.51	8.9%	0.2%
7	04	Suspension System	301.2	105.4	-154.90	-1.47	-1.48	35.0%	4.3%
8	05	Driveline System	183.8	20.4	38.01	1.86	1.89	11.1%	0.8%
9	06	Brake System	101.0	45.8	-148.92	-3.25	-3.35	45.4%	1.9%
10	07	Frame and Mounting System	267.6	23.7	-54.42	-2.30	-2.30	8.9%	1.0%
11	09	Exhaust System	38.1	6.9	-13.69	-1.97	-1.97	18.1%	0.3%
12	10	Fuel System	26.3	7.3	11.92	1.62	1.77	27.9%	0.3%
13	11	Steering System	32.5	8.5	-147.46	-17.44	-17.45	26.0%	0.3%
14	12	Climate Control System	20.3	1.9	14.71	7.59	7.59	9.5%	0.1%
15	13	Information, Gage and Warning Device System	1.6	0.2	0.66	2.66	2.97	15.7%	0.0%
16	14	Electrical Power Supply System	21.1	12.8	-172.73	-13.49	-13.44	60.6%	0.5%
17	15	In-Vehicle Entertainment System	2.2	0.0	0.00	0.00	0.00	0.0%	0.0%
18	17	Lighting System	9.6	0.4	-2.00	-5.18	-5.18	4.0%	0.0%
19	18	Electrical Distribution and Electronic Control System	33.6	8.5	61.44	7.26	7.27	25.2%	0.3%
20	00	Fluids and Miscellaneous Coating Materials	116.8	0.0	0.00	0.00	0.00	0.0%	0.0%
		a. Analysis Totals Without NVH Counter Measures →	**2454.4**	**560.9**	**-2073.82**	**-3.70**	**-3.69**	**n/a**	**22.9%**
		b. Vehicle NVH Counter Measures (Mass & Cost) →	0.0	-50.0	-150.00	**n/a**	**n/a**	**n/a**	**n/a**
		c. Analysis Totals With NVH Counter Measures →	**2454.4**	**510.9** (Decrease)	**-2223.82** (Increase)	**-4.35** (Increase)	**-4.35** (Increase)	**n/a**	**20.8%**

(1) Negative value (i.e., **-X.XX**) represents an increase in mass
(2) Negative value (i.e., **-$X.XX**) represents an increase in cost

Figure 2.47 Light Duty Pickup Truck Lightweighting Study Results

The individual technology mass and cost saving used to develop the system summaries listed in Figure 2.47 were used to develop EPA's cost curve for the light duty pickup truck lightweighting study, as shown in Figure 2.48. It should be noted that the blue squares are individual solutions and are not based on the cost curve technology points which lead to the red square solution point.

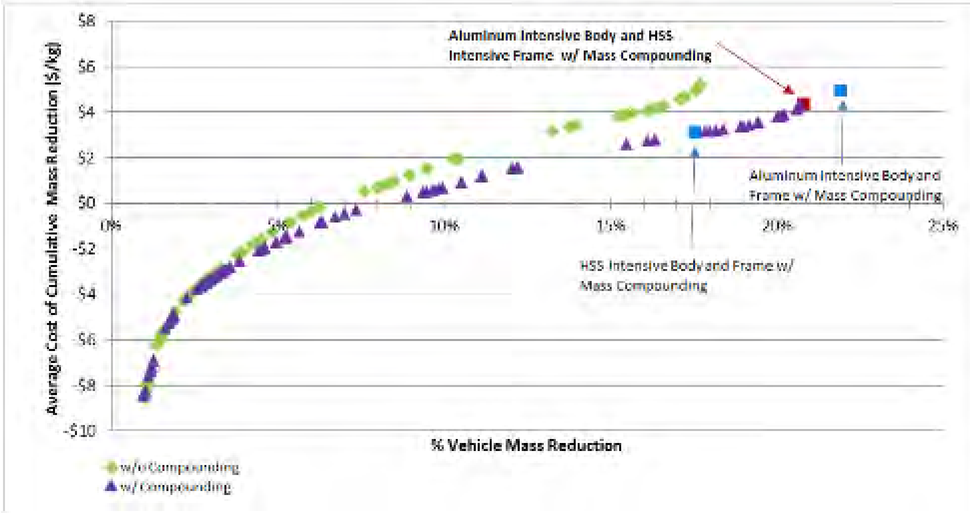


Figure 2.48 Light Duty Pickup Truck Lightweighting Cost Curve

The curve without compounding in Figure 2.48 (green curve) includes primary mass reduction ideas which do not depend on the vehicle being made lighter. The mass reduction ideas based on a resultant lighter vehicle are called secondary mass saving ideas and are based on components decreasing in size and hence material. In this study the engine was able to be downsized 7 percent due to the mass reduction in the vehicle design and still maintain the current towing and hauling capacities. The other systems that were reduced in size, while considering truck performance characteristics, included the transmission, body system group A (bumpers), suspension, brake, frame and mounting systems, exhaust, and fuel systems. The systems considered for secondary mass are included in Figure 2.49 and show the total 83.9kg mass save at $68.74 savings. Overall, the secondary mass savings are 17.6[TT] percent of the primary. The compounded curve in Figure 2.48 is the EPA light duty truck cost curve utilized in the development of the overall cost curve for light duty trucks described in Section 2.3.

[TT] % Secondary Mass = 560.9 compounded-83.9secondary =477kg primary, 83.9/477 = 17.6% secondary.

			Secondary Mass Savings (SMS) Impact by Vehicle System									
Item	System ID	Description	Base Mass "kg"	Mass Reduction with SMS "kg" (1)	Mass Reduction without SMS "kg" (1)	Incremental Mass Reduction from SMS "kg" (1)	Cost Impact NIDMC with SMS "$" (2)	Cost Impact NIDMC without SMS "$" (2)	Savings from SMS "$" (2)	Cost/ Kilogram NIDMC with SMS "$/kg" (2)	Cost/ Kilogram NIDMC without SMS "$/kg" (2)	Cost Savings/ Kilogram NIDMC from SMS "$/kg" (2)
1500 Series Chevrolet Silverado Pick-Up Truck												
1	01	Engine System	239.9	31.8	23.8	8.0	-92.83	-114.63	21.81	-2.92	-4.82	1.90
2	02	Transmission System	145.3	39.4	34.2	5.2	-96.57	-128.20	31.64	-2.45	-3.75	1.30
3	03A	Body System Group - A- (Body Sheetmetal)	574.7	207.1	190.7	16.4	-1194.86	-1125.15	-69.71	-5.77	-5.90	0.13
7	04	Suspension System	301.2	105.4	83.1	22.4	-151.90	-260.84	105.94	-1.47	-3.14	1.67
9	06	Brake System	101.0	45.8	43.9	2.0	-148.92	-167.87	18.95	-3.25	-3.83	0.58
10	07	Frame and Mounting System	267.6	23.7	0.0	23.7	-54.42	0.00	-54.42	-2.30	0.00	-2.30
11	09	Exhaust System	38.4	6.9	6.3	0.6	-13.69	-19.54	5.85	-1.97	-3.08	1.11
12	10	Fuel System	26.3	7.3	1.6	5.7	11.92	3.25	8.67	1.62	2.02	-0.40
		a. Analysis Totals Without NVH Counter Measures →	**1694.5**	**467.5**	**383.6**	**83.9**	**-1744.26** (Increase)	**-1813.00** (Increase)	**68.74**	**-3.73** (Increase)	**-4.73** (Increase)	**0.82**

(1) Negative value (i.e., -X.XX) represents an increase in mass
(2) Negative value (i.e., -$X.XX) represents an increase in cost

Figure 2.49 Light Duty Pickup Truck Lightweighting Study Secondary Mass

2.2.7.4.2 NHTSA Holistic Vehicle Mass Reduction/Cost Studies

To support the Midterm Evaluation, NHTSA funded two holistic vehicle mass reduction/cost studies. These studies are described in full detail in the Draft TAR. For complete information on these studies, please see Draft TAR Section 5.2.7.4.2 (Draft TAR page 5-176).

2.2.7.4.3 ARB Holistic Vehicle Mass Reduction/Cost Study

The California Air Resources Board funded Lotus Engineering on further analysis of in-depth cost and CAE, of the Phase 2 High Development of the Midsize CUV.[452] The project focused on the BIW design through CAE and more in-depth costing of the BIW. A full vehicle solution point was developed by adding the cost and mass save results of the BIW analysis to the cost and mass save information on the other vehicle systems from the Phase 1 work.[453] The report changed the original BIW design of 30 percent magnesium, 37 percent aluminum, 6.6 percent steel and 21 percent composites to one of 12 percent magnesium, 75 percent aluminum, 8 percent steel and 5 percent composites, shown in Figure 2.51. The report states that its BIW design reduced the number of parts from 419 parts in the baseline Venza to 169 parts in the low mass design. Specifically, the report states "By factoring in the manufacturability of the materials and designs into the fundamental design process, it is expected that … this type of design [will] be production ready in 2020."

The summary write-up for this work is contained within the LD GHG 2017-2025 FRM Joint Technical Support Document. A cost curve was not developed for this work. Values of cost and overall mass reduction were located in several areas of the report. The overall results, including all of the mass reduction items in the Phase 1 report and including powertrain were taken from Table 4.5.7.2.f. totaling 531.2kg reduced (31 percent of 1711kg) and the total cost was taken from the 4.6.1. Conclusions section of $342/vehicle cost save. The cost per kilogram for this solution is calculated as -$0.64/kg cost saved. This point, along with two other all aluminum vehicle solution points - one by NHTSA and the other by the Aluminum Association, helps to indicate the direction for additional mass reduction beyond the AHSS BIW/Aluminum closure solution on which the cost curve for the passenger car/Midsize CUV is based.

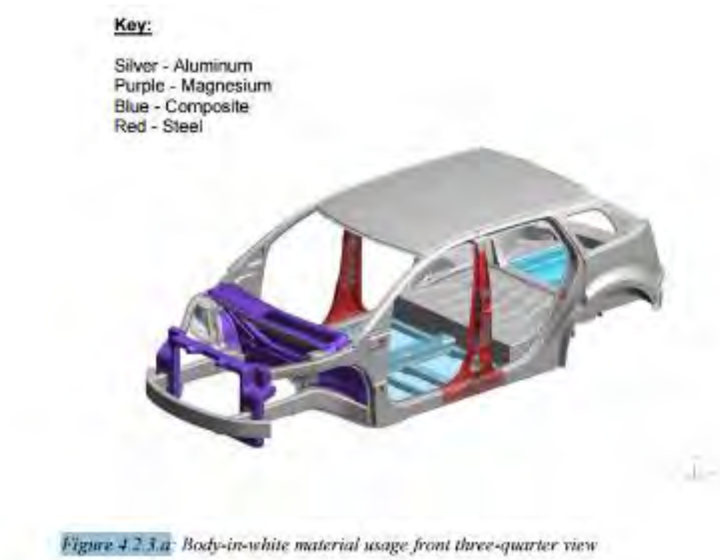


Figure 2.50 Phase 2 High Development BIW - Lotus Engineering

2.2.7.4.4 *Aluminum Association Midsize CUV Aluminum BIW Study*

The Aluminum Association funded a project with EDAG, Inc.[454] in 2012 to perform an aluminum substitution analysis in the BIW of the Midsize CUV work by EPA using the EPA CAE baseline model for the work. The baseline model was also developed by EDAG, Inc. The analyses utilized CAE crash safety and NVH verifications when determining the specifics, gauge and grade, of the aluminum to be utilized in the BIW (Figure 2.51).

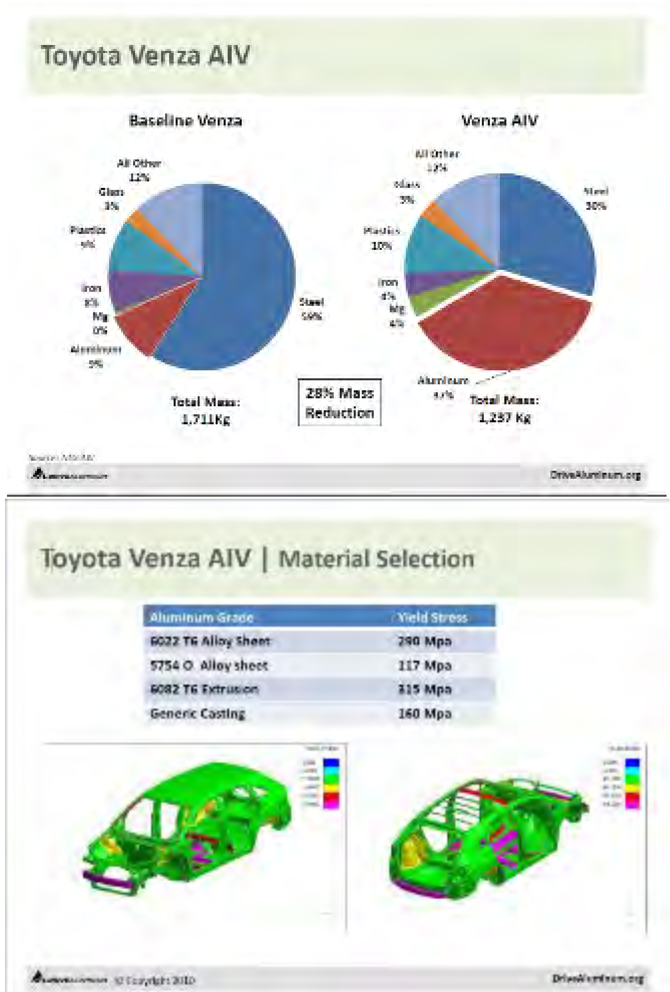


Figure 2.51 Midsize CUV Baseline vs Midsize CUV Aluminum Intensive Vehicle

Description	Estimated Mass Reduction "Kg"	Estimated Cost Impact "$"	Average Cost/ Kilogram "$/Kg"
Body Structure Subsystem			
Underbody Asy	19.8	-67.56	-3.41
Front Structure Asy	14.3	-121.84	-8.49
Roof Asy	14.6	-44.81	-3.07
Bodyside Asy	72.2	-306.60	-4.25
Ladder Asy	38.1	-235.53	-6.19
Bolt on BIP Components	3.2	-3.97	-1.23
Body Closure Subsystem			
Hood Asy	7.7	-27.70	-3.62
Front Door Asy	15.0	-21.65	-1.44
Rear Door Asy	11.3	-19.31	-1.70
Rear Hatch Asy	7.2	-21.21	-2.93
Front Fenders	2.0	-16.22	-8.25
Bumpers Subsystem			
Front Bumper Asy	2.3	-8.60	-3.82
Rear Bumper Asy	0.0	0.00	0.00
Totals	207.7	-895.01	-4.31

"+" = mass decrease, "-" = mass increase
"+" = cost decrease, "-" = cost increase

Figure 2.52 Summary Table of Mass Reduction and Cost for Aluminum BIW and Closure Components

Figure 2.52 lists the results from aluminum material substitution into the existing BIW and closures. When combined with the remaining mass and cost saved identified in the U.S. EPA Midsize CUV report, resulted in a $1.12/kg for 27.8 percent mass reduction for the entire vehicle, as shown in Table 2.16. This data point is included in the overall cost curve shown in Figure 2.45.

Table 2.16 Summary of the Automotive Aluminum 2025

	Multi-Material (MMV - EPA low dev)	Aluminum (AIV)
Body and Closure MR	-14%	-39%
Total Vehicle MR	-19.2%	-27.8% (-476kg)
Cost Impact	-$0.23/kg	$1.12/kg (+$534)*

*Note: Full Vehicle Mass Optimization

2.2.7.4.5 *Comparison of Data for Lightweight Car/CUV with Aluminum BIW*

The alternatives presented here are not reflected in the cost curves used in the present analysis, but are included to recognize that EPA does not expect a significant inflection upward in cost with mass reduction beyond what has been considered in this analysis. Several additional design solutions at higher levels of mass reduction with all aluminum BIW were developed using the Venza and Accord-based studies as starting points, as discussed in previous project descriptions, and solution points are shown with an extrapolation of the best fit Car/CUV cost curve (see Figure 2.53). The feasibility of achieving higher levels of mass reduction was also shown in the work by DOE/Ford/Magna, described in a following section, in which 23.5 percent mass reduction was achieved relative to a MY2013 Fusion[UU] for the Mach 1 design. The overall BIW design was multi-material with 64 percent aluminum, 29 percent steel and 7 percent hot stamping. A number of vehicles were built and crashed, including IIHS ODB, with acceptable results and several notes for further improvement in the BIW design to CAE predictive correlation were noted. Costing was not a part of this project; however, the SAE paper states "multi-material automotive bodies can achieve weight reduction with cost effective performance." [455]

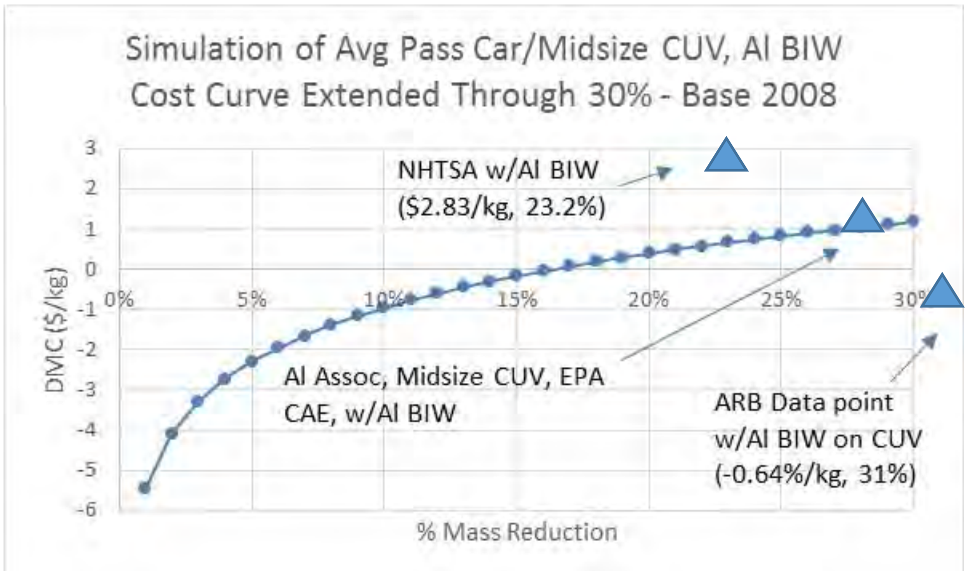


Figure 2.53 Car/CUV DMC Curve Extended to Points with Aluminum BIW

Figure 2.53 shows two points for the CUV aluminum intensive solution. One point is from the ARB-sponsored study by Lotus Engineering[456] and one point is from the Aluminum Association study through EDAG.[457] The ARB full vehicle data point with optimized BIW design and reduction of BIW components is 531kg (31 percent) mass reduction at -$0.64/kg. The Aluminum Association study of an all-aluminum BIW, based on material replacement into the CAE model from the original U.S. EPA Midsize CUV study, resulted in a total vehicle solution of $1.12/kg at a total of 476kg (27.8 percent) mass reduced. NHTSA studied the aluminum intensive vehicle design for the passenger car (based on the MY2011 Accord) and the result is a point at $2.83/kg for 23.2 percent.

Table 2.17 shows the detailed results of the studies. The cost/kg estimate for the NHTSA study is likely overestimated given the recent reduction in the commodity price for aluminum. The 2001 JOM source document used for the cost estimate indicates that costs have very likely

[UU] The MY2013 Fusion was one redesign beyond the 2008 era Fusion. The base vehicle is approximately 250 lbs heavier and the top trim is approximately 100 lbs heavier in 2013 compared to 2008. The 2013 Fusion is approximately 2.80sq ft larger in footprint compared to the 2008 era Fusion and slightly taller and wider overall. Several safety features were also included. (https://en.wikipedia.org/wiki/Ford_Fusion_(Americas)) decreased since this work was completed.[VV,458] The Lotus Engineering and EDAG are similar and achieve results for three major systems which are only 6kg apart (201.7kg v 207.7kg respectively). The differences between the two projects include the BIW designs used and the resultant estimated costs. The EDAG study used the existing BIW design and the materials of aluminum alloy sheet, extrusion and casting. The Lotus Engineering solution also utilized the different aluminum components while optimizing component aggregation as only 169 components were used in the BIW compared to the original 419 and significant savings with the new manufacturing processes were assumed.

Table 2.17 Three Aluminum Intensive Vehicle Design Summary - DMC ($), %MR and $/kg

Aluminum BIW, Closures, Chassis	2012 ARB/Lotus (midsize CUV-1711kg)		2012 Al Assoc/EDAG (midsize CUV -1711kg)		2012 NHTSA/Electricore/ EDAG (Pass Car-1480kg)	
	Mass save (kg)	Cost ($)	Mass save (kg)	Cost ($)	Mass save (kg)	Cost ($)
BIW	140.7	239	162.2	780	113	782
Closures/Fenders	59	-381	43.2	106	44	153.7
Bumpers	2	9	2.3	8.6	-	-
SUB-TOTAL	201.7	-133	207.7	894.6	157	935.7
Total Vehicle	530	-342	464*	+520*	343.6	971.9
$/kg	-$0.64/kg		$1.12/kg		$2.83/kg	

Note: *adjusted for changes in the EPA baseline Midsize CUV cost curve into which the aluminum BIW was placed

2.2.7.4.6 DOE/Ford/Magna MMLV Mach 1 and Mach 2 Lightweighting Research Projects

The Multi Material Lightweight Vehicle (MMLV) project was initiated in 2012 by the Department of Energy and co-funded by Magna International and Ford Motor Corporation under the project number DE-EE0005574. The objectives of the project included identifying 25 percent (Mach 1) and 50 percent (Mach 2) vehicle mass reduction packages. This work was peer reviewed through the DOE AMR and the SAE publication processes. The "Multi-Material Lightweight Vehicles" presentation, which was a combination of the Mach 1 and Mach 2 projects, was peer reviewed at the 2015 DOE AMR in front of a panel of experts in the field and the results of the peer review were included in the final report for the DOE AMR.[459] The project received a weighted average score of 3.77 out of 4.0 and was measured on reviewer questions related to approach, technical accomplishments, collaborations, and future research. The results were also presented in a number of SAE papers and hence reviewed through the SAE publication process.

The DOE/Ford/Magna project developed the lightweight vehicle solutions off of a MY2013 Ford Fusion platform (used to represent a 2002 Ford Taurus). Results include 23.5 percent for the Mach 1 design. Seven vehicles were built and the vehicles, and certain components, were tested under a series of durability tests. New technologies of composite fiber springs, carbon fiber wheels, seat back frame, and the multi-material body structure were included in the

[VV] Investigation into the supporting documentation for the analysis revealed that the information was taken from a 2001 article in the Journal of Minerals, Metals and Materials Society. The article states "In fact, design developments by Audi already have resulted in significant cost reductions between its first- and second-generation vehicles. These have come about through parts consolidation, process substitutions, and part simplification."

durability tests. For the Mach 2 design, 50 percent mass reduction is achieved however the vehicle is not market viable due to extensive de-contenting and use of materials that are not yet ready for full volume production including composite "tub" package tray and roof. A comparison of the MMLV structures weight for BIW, Closure, Chassis and Bumper is displayed in Figure 2.54.

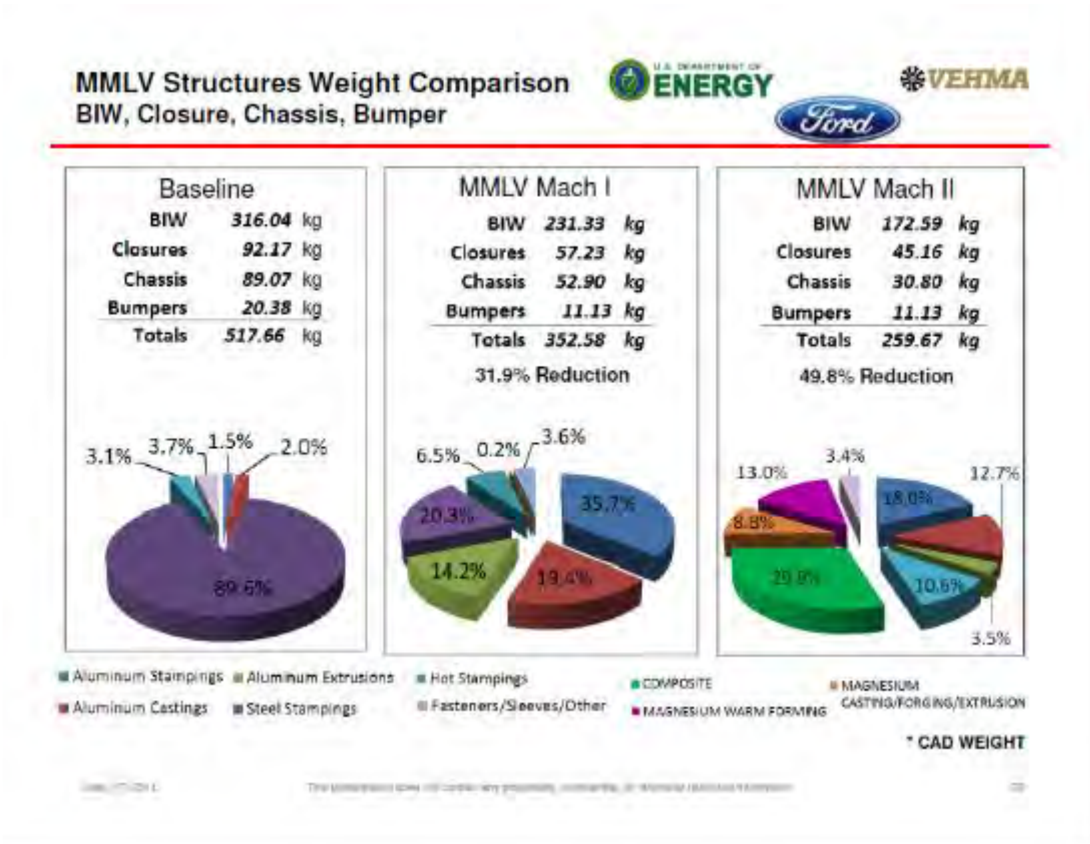


Figure 2.54 MMLV Structures Weight Comparison BIW, Closure, Chassis, Bumper[460]

Gaps identified by the MMLV projects (I and II) include those listed in Table 2.18.

Table 2.18 Gaps Identified by MMLV Project

Topic	GAP
Steel	Improved coatings on ultra-high strength steels for multi material applications
Aluminum	Increased die life and bi-metallic (inserts, etc.) for Al die castings plus low cost 7000 series aluminum sheet and extrusions
Magnesium	High volume warm forming, hemming, class A finish, plus improved die life and bi-metallic inserts in high pressure vacuum die casting
Carbon Fiber Composites	Material characterization for CAE, joining, corrosion, paint, class-A finish
Multi Material Vehicles	Corrosion mitigation strategy including universal equivalent of phosphate (or eqiuv) bath for any mix of steel, aluminum and magnesium before e-coat and paint
	Joining methods with corrosion mitigation
	Aluminum rivet, high hardness, high strength

	Alternative NVH treatments for lightweight panels sheet metal and glazings
	Design for disassembly, end of life, for reclaiming, recycling

No cost analysis was performed for the Mach 1 study. A 40-45 percent MR cost analyses from the base 2013MY vehicle was completed under a separate DOE project, through Idaho National Laboratories performed by IBIS Associates Inc., and results indicate the cost of carbon fiber must decrease in order to make the technology viable for mass market vehicles.[461] This project is described in 2.2.7.4.7.

A second cost study was funded by DOE Office of Nuclear Energy and completed in June 2016. The title was "Vehicle Lightweighting: Mass Reduction Spectrum Analysis and Process cost Modeling" by IBIS Associates, Energetics and Idaho National Laboratory. The objectives of this report were to "Assess the multiple strategies addressed in the earlier phases in terms of weight reduction, cost premiums and risk factors in order to establish a prioritized spectrum of lightweighting opportunities." And "Apply process technical Cost models (TCMs) to priority lightweight material manufacturing technologies to evaluate cost structures and understand the relative leverage of key cost drivers. The processes targeted were aluminum extrusion, magnesium sheet forming and carbon fiber composite molding." This study examined mass savings and costing for a range of technologies from a number of lightweighting studies available as of 2015.

2.2.7.4.6.1 Mach I

The MMLV Mach I project achieved 364 kg (23.5 percent) mass reduction from the baseline weight of the 2013 Ford Fusion (representing a 2002 Ford Taurus). Seven prototype vehicles were built and these vehicles were used to conduct a number of test such as, corrosion, durability, NVH (noise vibration harshness), and crash. Maintaining performance and capabilities, along with safety and durability were also goals of the MMLV. All parts used in the MMLV are either low volume or high volume production capable up to 250,000 vehicles per year. The Mach I mass reduction was achieved using materials such as aluminum, carbon fibers, magnesium, and high strength steels. Results of the Mach I project were presented in 13 SAE papers.[462,463,464,465,466,467,468,469,470,471,472,473,474]

The Mach I project group presented an estimate of the fuel economy improvement at the 2015 SAE World Congress 2015 as being an increase to 34 mpg from 28 mpg. This change in fuel economy was estimated by taking the fuel economy of a Ford Fiesta (which is the equivalent weight of the lightweight Mach-I) and comparing to the 2013 Ford Fusion. The fuel economy numbers were from fueleconomy.gov. Key requirements of durability, safety, and Noise Vibration Harshness (NVH) were also met within the Mach I design as illustrated in a report presentation at the 2015 DOE AMR.[475] All components of the MMLV were specifically chosen for optimal weight reduction without shorting on performance or technicality.

Five subsystems of the Mach I compared to the baseline 2013 fusion of full body mass reduction.[475]

- The body-in-white (BIW) and closures contributed 76 kg (4.9percent) to the overall vehicle mass reduction. The baseline 2013 BIW is 326 kg and the Mach-I BIW is 250 kg. The 2013 Fusion BIW is steel intensive, and the Mach-I design included advanced high strength steels were integrated for use as primary safety structures like crush rails, B-pillars, and selected cross car beams. Closures in the Mach 1 were aluminum intensive. The transition from steel to aluminum is also the primary design strategy for the light weighting of the deck lid, and front fenders, as well as the side door structures and hinges. Also, chemically foamed plastics were used in the door design as trim.

- Body Interior and Climate Control consists of the seats, floor components, instrument panel/ cross car beam (IP/CCB), and climate control system which contributed 28 kg (1.8 percent) to the overall vehicle mass reduction. The IP/CCB decreased in part count from 71 to 21, new material design involved carbon fiber reinforce nylon from the baseline welded assembly of steel stampings and tubes. The material selection of the seat structures was carbon fiber reinforced nylon composite compared to the baseline steel stampings and tubes.
- Chassis subsystem reduced its total mass by 98 kg (6.3 percent) to the overall vehicle mass reduction. The major components identified in the Mach 1 subsystem include hollow coil springs, carbon fiber wheels, and tires with a tall and narrow design, hollow steel stabilizer bars, aluminum sub frames, control arms and links.
- The powertrain subsystem was reduced by 73 kg (4.7 percent) to the overall vehicle mass reduction. The baseline engine is a 1.6 liter four-cylinder gasoline turbocharged direct injection (EcoBoost) with a six-speed automatic transmission. The Mach-I design has a 1.0 liter three-cylinder gasoline turbocharged direct injection (Fox EcoBoost) with a mass reduced six-speed automatic transmission. The use of carbon fiber within this subsystem encouraged mass reduction and include components such as the engine oil pan.
- The electrical subsystem achieved a 10 kg (0.64 percent overall vehicle mass reduction). A few adjustments were made to accomplish this number. The battery was switched to a lithium ion 12-volt start battery from the baseline lead-acid battery. The change of the battery achieved 5 kg mass reduction. Also, copper electrical distribution wiring was replaced with aluminum conductors meeting a 4 kg mass reduction. The remaining 1 kg mass reduction was achieved by small adjustments to the speakers, alternator, and the starter motor.

The Mach-I used computer aided engineering (CAE) for many safety simulations in addition to performing a number of actual vehicle safety crashes. Seven MMLV Mach-I vehicles were built and selectively tested. Seven different validation tests were completed as listed in Table 2.19.

Table 2.19 Safety Tests Performed on the Mach-I.

VEHICLE	TESTING
Test Buck	Body-in-White + Closures + Bumpers + Glazing + Front Subframe - Body-in-Prime NVH modes, global stiffness, attachment stiffness, selected Durability
Durability A	DRIVABLE, full MMLV content with Fusion powertrain - MPG Structural Durability, Square Edge Chuckhole Test for Wheels and Tires

Corrosion A Traditional Surface Treatments	DRIVABLE, with alternative surface treatment and paint process - MPG Corrosion R-343. Humidity soaks and salt spray etc.
Corrosion B MMLV Alternative Surface Treatments	DRIVABLE, with traditional surface treatment and paint process - MPG Corrosion R-343. Humidity soaks and salt spray etc.
Safety A	NON-Drivable, most MMLV content, without carbon fiber instrument panel - Low Speed Damageability test (front) Right Hand (passenger) side - IIHS Front ODB 40% Offset 40 mph, Left Hand (driver) side - Side Pole Test on Right Hand (passenger) side (FMVSS 214)
Safety B	NON-Drivable, most MMLV content, without carbon fiber instrument panel - NCAP Frontal 35 mph rigid wall, then 70% Offset Rear Impact (FMVSS 301)
NVH + Drives	DRIVABLE, full MMLV content with downsized and boosted powertrain, 1.0-liter I3 EcoBoost, gasoline turbocharged direct injection engine plus six-speed manual transmission - Wind Tunnel, Rough Road Interior Noise, Engine & Tire Noise, Ride & Handling

The overall outcome of the safety and durability tests provided assurance a multi-material lightweight vehicle was successful. Noise Vibration Harshness was tested in a high frequency range of 200-10000 Hz and fell within acceptability but slightly short of requirements. Durability test classified the Mach-I as a durable vehicle and showed no major cracking or durability incidents in the test mileage. Frontal crash safety tests showed that nine parts withstood the test at a good level. Table 2.20 is a list of the parts that performed the best. The carbon fiber wheels had one issue in the durability test with the outer coating on the carbon fiber, however it was solved and the wheel is currently planned for the Shelby Mustang. The composite fiber springs performed better than expected and it is understood that they are in production, or planned for production, in the Audi A6 Ultra Avant and the Renault Megane Trophy RS vehicles. The durability issue for the composite fiber wheels was solved and the improved wheels are being employed in the Shelby Mustang. Some new discoveries were made including the near zero mass add for NVH considerations and corrosion concerns will be better addressed with a correct amount of sealant and the proper choice of nuts and bolts in the multi material vehicle design.

Table 2.20 Mach-I Components to Maintain Frontal Crash Performance.

PART	MATERIAL
Front bumper	Extruded aluminum
Crush Can	Extruded aluminum
Subframe	Cast and extruded aluminum
Shock Tower	Cast aluminum
Coil Spring	Chopped glass fiber composite
Wheel	Woven carbon fiber composite
A-Pillar joint node	Cast aluminum
Windshield	Chemically toughened laminate
Seat frame	Woven carbon fiber composite

2.2.7.4.6.2 Mach 2

The goal of the Mach 2 project was to create a lightweight design that achieved 50 percent mass savings from the 2013 Ford Fusion (representing a 2002 Ford Taurus). This amount of mass reduction is forward looking and of limited use for the time frame considered for this Proposed Determination (2022-2025) which has a top application of 20 percent mass reduction.

The project achieved 51.1 percent (798kg) mass reduction with a significant degree of mass reduction using materials and processes that have some initial research but not ready for high volume. Significant vehicle de-contenting was employed which included items from air conditioning to thinning the windows and the resultant vehicle was not marketable.

The vehicle technologies for the BIW and Closures includes carbon fiber and composites as seen in Figure 2.55. However, the CAE inputs were not mature for the materials and as a result the outputs were insufficient. CAE information included cards for stiffness, durability, and fatigue analyses. In terms of production, the composite material and manufacturing infrastructure was also not mature for automotive volumes. The carbon fiber and composite panels were not deemed acceptable for Class A surfaces and as a result aluminum or magnesium sheet products were chosen for the BIW and closure applications.

Table 2.21 Mach II Design Vehicle Summary[475]

System	Technology	Material/Approach
Body and Closures	Body	Composite intensive
	Closures	Magnesium
	Windows	Reduced Thickness
Interior & Climate Control	Seats	Carbon fiber seats with reduced function
	IP	Carbon fiber composite
	Reduced content	No bins, center console, air conditioner, etc.
Chassis	Subframes	Cast magnesium
	Coil Springs	Composite
	Reduced capacity	For reduced weight cargo and towing
Powertrain	Engine	1.0L 3 cyl naturally aspirated Remove turbocharger and intercooler Material change
	Transmission	Reduced capacity manual
Electrical		Eliminate content and features
		Reduced battery, alternator, wiring

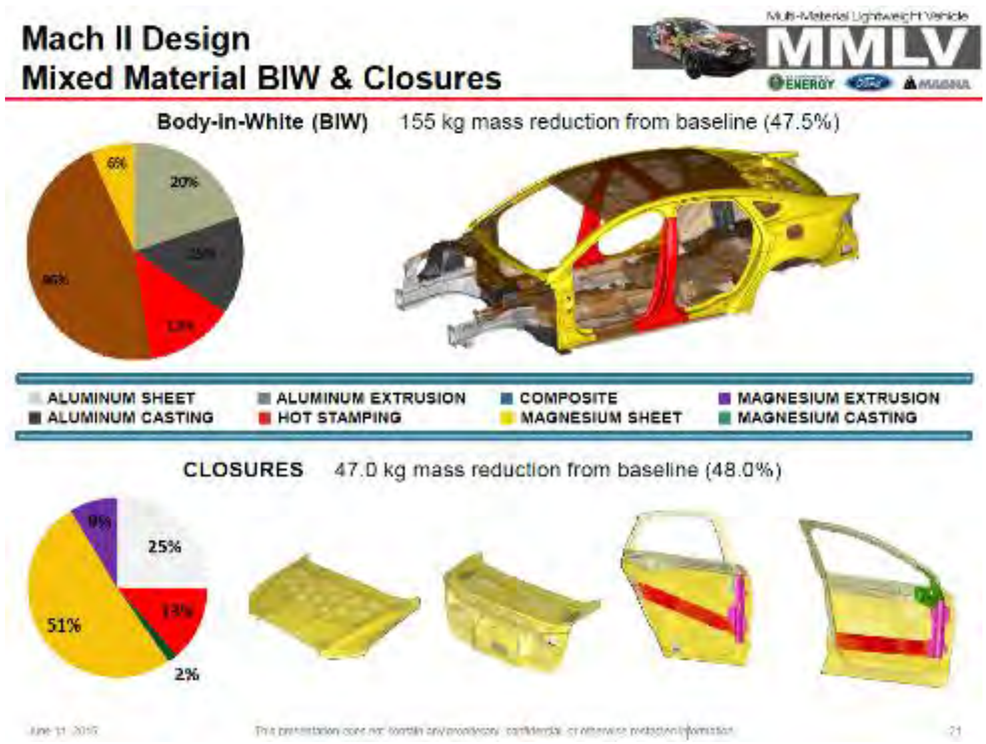


Figure 2.55 Mach II Mixed Material BIW and Closure Design (brown is carbon fiber)[475]

2.2.7.4.7 Technical Cost Modeling Report by DOE/INL/IBIS on 40 Percent-45 Percent Mass Reduced Vehicle

The U.S. Department of Energy's Vehicle Technologies Office Materials Area funded a study to provide cost estimates and assessment of a 40 percent and 45 percent weight savings on a North American midsize passenger sedan based on the work of the Mach 1 and Mach 2 lightweighting projects. The title of the report is "Vehicle Lightweighting: 40 percent and 45 percent Weight Savings Analysis: Technical Cost Modeling for Vehicle Lightweighting"[476]. This work was peer reviewed through the 2015 DOE AMR "Technical Cost Modeling for Vehicle Lightweighting". Results of the peer review were included in the final report for the DOE AMR.[477]

The goal of the work was to achieve 40 percent-45 percent mass reduction relative to a standard North American midsize passenger sedan at an effective cost of $3.42/lb. This study utilized existing mass reduction and/or cost studies including those from FEV, Lotus Engineering, DOE Mach 1 and Mach 2. The Executive Summary to this report states "The analysis indicates that a 37 to 45 percent reduction in a standard mid-sized vehicle is within reach if carbon fiber composite materials and manufacturing processes are available and if customers will accept a reduction in vehicle features and content, as demonstrated with the Multi-Materials and Carbon Fiber Composite-Intensive vehicle scenarios."

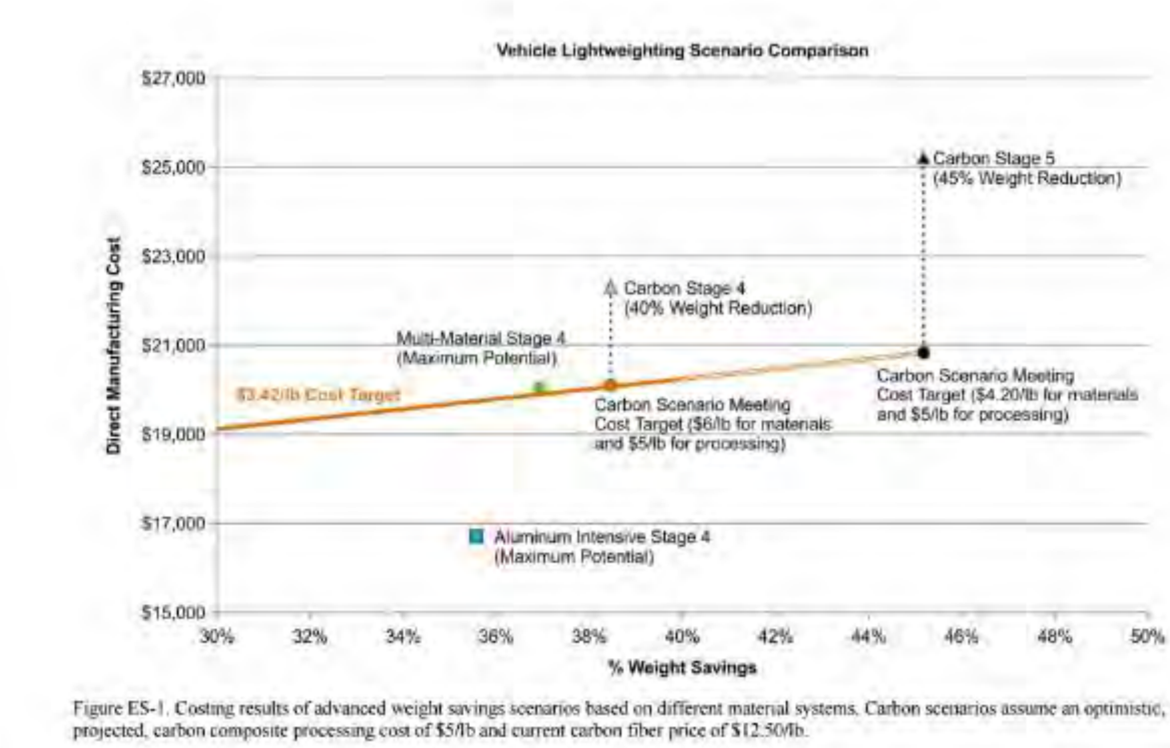


Figure 2.56 Technical Cost Modeling Results for 40 Percent to 45 Percent Lightweighting Scenario (Based on Mach 1/Mach 2 Project Technologies)

2.2.7.4.8 *<u>Mass Reduction Spectrum Analysis and Process Cost Modeling Report by DOE/IBIS/Energetics/INL</u>*

A cost study funded by the DOE Office of Nuclear Energy and completed in June 2016 was presented at the 2016 DOE Annual Merit Review.[478] The objectives of this report were to "Assess the multiple strategies addressed in the earlier phases in terms of weight reduction, cost premiums and risk factors in order to establish a prioritized spectrum of lightweighting opportunities," to "process technical cost models (TCMs) to priority lightweight material manufacturing technologies to evaluate cost structures and understand the relative leverage of key cost drivers. The processes targeted were aluminum extrusion, magnesium sheet forming and carbon fiber composite molding." This study examined mass savings and costing for a range of technologies from a number of lightweighting studies available as of 2015.

The findings of the study are threefold:

1. "Low Risk strategies that involve well understood materials and processes can be employed in the near-term to reduce the overall vehicle weight of a conventional North American midsize vehicle by up to 17 percent with cost of weight savings from $0-$2.00/lb. This is achieved with increased aluminum, moderate price premium and low technical risk."[478]

2. "Medium Risk strategies can be used to reduce the overall vehicle weight up to a total of 27 percent with a best case cost of weight savings still about $2.00/lb. Extensive lightweighting needed: Increased magnesium, component redesign, system downsizing, lightweight interior materials and glazings."[478]

3. "High Risk strategies are needed to achieve the highest levels of weight reduction that approach 45 percent overall vehicle weight savings with cost of savings up to $7.00/lb under optimum conditions. Requires: carbon fiber at significantly reduced cost per pound, Extensive use of Mg, advanced electrical and interior systems, consumer acceptance of some de-contenting."[478]

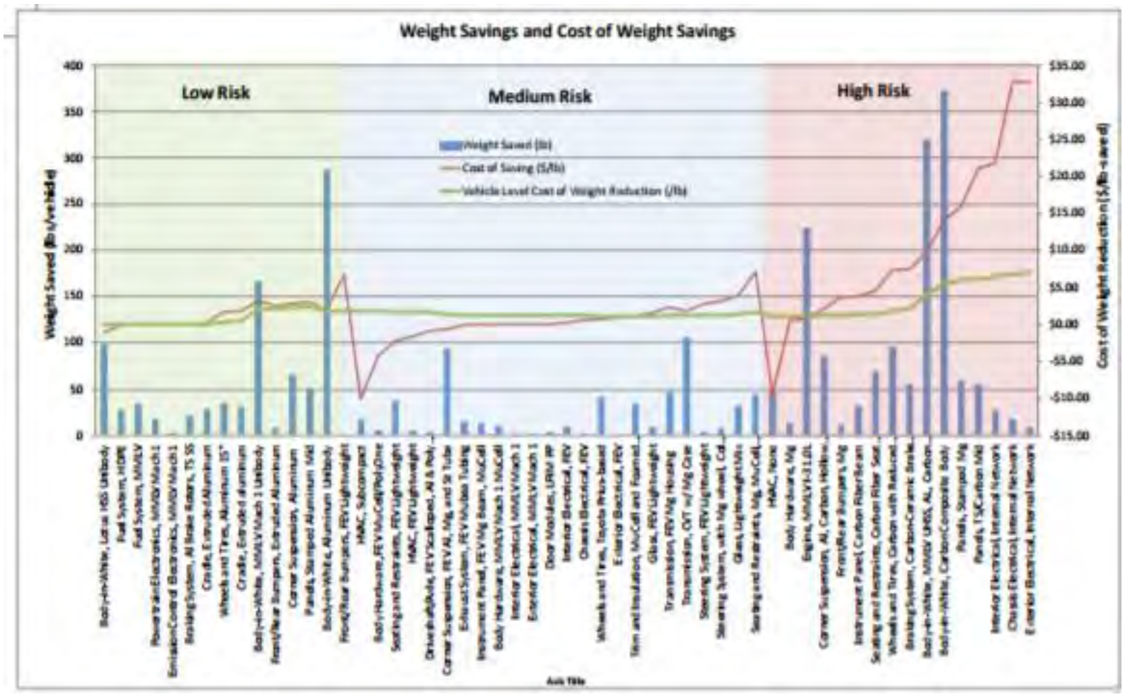


Figure 2.57 Results for Weight Reduction Strategies by Risk Factor and Cost of Weight Savings[478]

2.2.7.4.9 *Studies to Determine Potential Mass Addition for IIHS Small Overlap*

One of the requirements of the IIHS Top Safety Pick is to meet the IIHS small overlap (SOL) crash test (see Figure 2.58). The IIHS SOL test is designed to reproduce what happens when the front corner of a vehicle hits another vehicle or an object like a tree or utility pole. Estimating the mass impact to succeed this test can vary widely among different types of vehicles. The structure of the vehicle must be redesigned in order to design load paths such that the passenger compartment remains sound throughout the crash event.

Figure 2.58 Post-test Laboratory Vehicle of IIHS Small Overlap Test

Two studies were funded to examine the mass add to existing vehicle study models. NTHSA funded the passenger car study using their LWV model and Transport Canada funded the light duty truck study using the LDT model from the EPA light duty pickup truck study. All of the CAE modeling, from the base studies to the IIHS small overlap studies were performed by two separate groups within EDAG, Inc. The results of these studies are described in the following sections.

2.2.7.4.9.1 NHTSA Mass Add Study for a Passenger Car to Achieve a "Good" Rating on the IIHS Small Overlap

The analysis of the IIHS Small Overlap resultant mass add for a variety of unibody passenger car vehicle classes are included in the February 2016 report "Update to Future Midsize Lightweight Vehicle Findings in Response to Manufacturer review and IIHS Small-Overlap Testing."[479] In order to improve the structural performance during the IIHS SOL test, several options were considered and implemented using a detailed LS-DYNA crash model that was originally part of the NHTSA LWV study. Changes regarding the SOL test include reinforcement of major areas in the body structure and were designed for easy manufacturability and assembly into the body structure. The findings for the IIHS SOL solution was a mass addition of 6.9 kg and $26.88 in cost.

The report also includes the IIHS mass add results for a range of unibody vehicle classes as shown in Table 2.22 (MY2010) and Table 2.23 (MY2020). The overall Light Duty Vehicle Average is based on a straight average of the values for each vehicle class. The report also notes that estimated mass increases for 'body on frame' vehicles should be further reviewed due to a differing body structure design. This was done in Transport Canada's evaluation of the 2011 Silverado 1500 discussed in the section following this section.

Table 2.22 Estimated Mass Increase to Meet IIHS SOL for 2010 Vehicle Classes

	2010 Vehicle Class Average			
Vehicle Class	Curb Vehicle Weight (kg)	Test Vehicle Weight (kg)	Increase in mass to meet IIHS SOL (kg)	Curb Vehicle Weight with IIHS SOL Changes (kg)
Sub-Compact Car	1261	1411	7.4	1268
Compact Car	1345	1495	7.8	1353
Mid-Sized Car	1561	1711	8.9	1570
Small SUV/LT	1592	1742	9.1	1601
Large Car	1752	1902	9.9	1762
Mid-Sized SUV/LT	1916	2066	10.8	1927
Minivans	2035	2185	11.4	2046
Large SUV/LT	2391	2541	13.3	2404
Light Duty Vehicle Average	1732	1882	9.8	1741

Table 2.23 Estimated Mass Increase to Meet IIHS SOL for 2020 Vehicle Classes

	2020 Vehicle Class Average			
Vehicle Class	Curb Vehicle Weight (kg)	Test Vehicle Weight (kg)	Increase in mass to meet IIHS SOL (kg)	Curb Vehicle Weight with IIHS SOL Changes (kg)
Sub-Compact Car	1055	1205	6.3	1062
Compact Car	1119	1269	6.6	1125

Mid-Sized Car	1294	1444	7.5	1302
Small SUV/LT	1318	1468	7.7	1326
Large Car	1453	1603	8.4	1462
Mid-Sized SUV/LT	1632	1782	9.3	1641
Minivans	1689	1839	9.6	1699
Large SUV/LT	1962	2112	11.0	1973
Light Duty Vehicle Average	1440	1590	8.3	1449

2.2.7.4.9.2 Transport Canada Mass Add Study for a Light Duty Truck to Achieve a "Good" Rating on the IIHS Small Overlap

Transport Canada funded a project with EDAG, Inc.[480] in which a body on frame 2013MY Silverado 1500 light duty pickup truck (designed in 2007) was evaluated and modeled in order to achieve a "Good" rating on the IIHS small overlap crash test. The study utilized the work done by FEV in EPA's light-weighting light duty pickup truck study and has been peer reviewed through EPA's peer review process.

The baseline CAE model was used to correlate the modeled performance with an actual impact test conducted at Transport Canada's Motor Vehicle Test & Research Centre in Blainville, Québec. The state of the truck from the barrier impact is shown in Figure 2.59. A number of components were material tested through the assistance of Natural Resources Canada's CanmetMATERIALS facility in Hamilton, Ontario. This was done in order to ensure that the most accurate materials properties were being input into the baseline model at the start of the process and in order that the CAE modeling could reproduce the video from the actual crash test as closely as possible. The baseline model was modified with failure criteria and timing of respective components involved in the IIHS small overlap test. Figure 2.60 shows the baseline model correlating to the baseline truck crash event.

Figure 2.59 MY2013 Silverado 1500 IIHS Small Overlap Test Crash Before and During

Figure 2.60 Converting the Actual Crash Event to a Model

Development of the light duty truck design modifications to the baseline structure began with research on existing IIHS crash results including those from the GM Equinox, Mercedes ML, and design information on the 2014MY Silverado 1500 and the 2015MY Ford F150 which had been released before the conclusion of this project. A solution for a “Good” rating on the IIHS small overlap crash test was determined for the steel intensive vehicle in order to highlight the areas for improvement in the lightweight model. The mass add for this design was not optimized for the minimum mass add that would still achieve a "Good" rating.

To develop the lightweight model mass add to the “Good” rating on the IIHS small overlap, the vehicle lightweighting ideas from the original U.S. EPA lightweight light duty truck project were first adopted onto the vehicle. The solution from the baseline vehicle was then optimized and the mass add determined. The report states "Like the original EPA Project cab, the T5-LW (light-weighted) cab exploited the low density and manufacturing methods specific to Aluminum, …Extrusions and castings were used to meet and exceed the static bending and torsion requirements with mass efficient solutions." The components in the area of the crash (including suspension and wheel) were not changed to aluminum for the failure information for the aluminum components were not available. The resultant light-weighted model before and after IIHS small overlap crash is illustrated in Figure 2.61. The passenger compartment stays in tact as shown.

Figure 2.61 Light Weighted Model in the IIHS Small Overlap Crash Test

The accelerations for the dummies will change based on the stiffer passenger compartment which doesn't allow the extreme intrusions in the baseline model. The report contains a comparison of the Velocity (m/s) at CoG X-velocities for the T4-GA LDT model and other production vehicles with "Good" IIHS small overlap results and the results are similar. The T5-LW results are very similar to the T4-GA results. The report concludes that "the pulse response is considered reasonable and it is expected that a modern restraints system could be tuned to manage the vehicle response." [480]

The IIHS Small Overlap Rating is based on dummy injury criteria as well as vehicle intrusion in specified locations within the vehicle. Figure 2.62 illustrates how the light-weighted model (T5-LW) compares to the baseline model (T3-BL) along with the results from the original crash test (TC13-018). The light-weighted model, with the countermeasures resulting in the addition of 17kg relative to the baseline model, achieves a Good rating in the intrusion part of the evaluation.

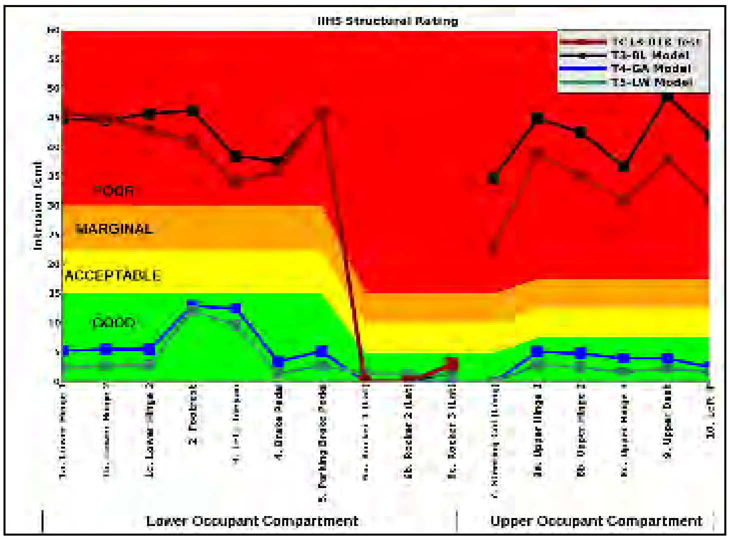


Figure 2.62 Results of the Project Models from Baseline to Light Weighted on the IIHS Small Overlap[480]

2.2.7.5 Potential Lightweight Recyclable Composite Fiber Material

A new recyclable thermoset technology was presented at the 2016 GALM UK conference.[481] While thermoset and thermoplastic technologies (plastics, composite fiber, etc.) provide lightweighting potential, there are several concerns over their increased use. Topics such as emissions during production and limited scrap/end of life recycling for thermoplastics with no potentials for thermoset recycling. Two milestones were achieved this year which may bring this material into the price range for consideration by OEMs in the future. First, a new technology developed at the University of Colorado Department of Chemistry and Biochemistry Materials Science and Engineering Program provides possibilities for a thermoset material that addresses a number of issues currently present in composite fiber usage for high volume vehicle production. The startup company Mallinda[482] is still in material development; however, noted characteristics of the material include: eliminate curing, improved manufacturing economics, enabling composite thermoforming, reduced manufacturing cycle time, re-moldable, solvent free for heat-induced vitrification. The material has chemically reversible polymerization potential and as such is closed-loop recyclable which reduces scrap. A ratio of 33 percent recyclable material and 67 percent new material is used to make new product. The material can also be repaired and can be used to repair other plastics/composites. Mallinda received a $750k grant for reusable carbon-fiber composite from the Phase II funding by the National Science Foundation's Small

Business Innovation Research program (SBIR).[483] Mallinda is also working within Cyclotron Road[484] which is a home for entrepreneurial researches to advance technologies until they can succeed beyond the research lab. The purpose of Cyclotron Road is to support critical technology development and help identify the most suitable business models, partners, and financing mechanisms for success.

Second, composite fiber material developed with this thermoset technology will require low cost carbon fibers. Presenters at 2016 GALM UK identified the limitations of current carbon fiber production including expense of producing the material and time to build production sufficient for automotive use. The Oakridge National Laboratory[485] announced in March of 2016 that they have made great strides in advancing carbon fiber technology. The March 2016 article states "Researchers at the Department of Energy's Oak Ridge National Laboratory have demonstrated a production method they estimate will reduce the cost of carbon fiber as much as 50 percent and the energy used in its production by more than 60 percent."[486] These two technologies used together, along with repair and recycling potentials, may put a composite fiber material within price range of OEM considerations in the future.

2.2.8 State of Other Vehicle Technologies

2.2.8.1 Electrified Power Steering: State of Technology

Compared to conventional hydraulic power steering, electrified power steering can reduce fuel consumption and CO_2 emissions by reducing overall accessory loads. Specifically, it reduces or eliminates the parasitic losses associated with belt-driven power steering pumps which consistently draw load from the engine to pump hydraulic fluid through the steering actuation systems even when the wheels are not being turned. Power steering may be electrified on light duty vehicles with a standard 12V electrical system; however, electric power steering could benefit from a 48V vehicle architecture by reducing electrical current and allowing higher steering loads. Electrified power steering is also an enabler for vehicle electrification since it provides power steering when the engine is off.

Power steering systems can be electrified in two ways. Manufacturers may choose to completely eliminate the hydraulic portion of the steering system and provide electric-only power steering (EPS) or they may choose to move the hydraulic pump from a belt driven configuration to a stand-alone electrically driven hydraulic pump. The latter system is referred to as electro-hydraulic power steering (EHPS).

The Draft TAR noted that EPS has been successfully implemented on all light duty vehicle classes (including trucks) with a standard 12V electrical system, eliminating the need to consider EHPS on larger vehicles. For the cost and effectiveness assumptions EPA has used in this Proposed Determination analysis, see Chapter 2.3.

2.2.8.2 Improved Accessories: State of Technology

The accessories on an engine, including the alternator, coolant and oil pumps are traditionally mechanically-driven. A reduction in CO_2 emissions and fuel consumption can be realized by driving them electrically, and only when needed ("on-demand").

Electric water pumps and electric fans can provide better control of engine cooling. For example, coolant flow from an electric water pump can be reduced and the radiator fan can be shut off during engine warm-up or cold ambient temperature conditions which will reduce warm-up time, reduce warm-up fuel enrichment, and reduce parasitic losses.

Indirect benefit may be obtained by reducing the flow from the water pump electrically during the engine warm-up period, allowing the engine to heat more rapidly and thereby reducing the fuel enrichment needed during cold starting of the engine. Further benefit may be obtained when electrification is combined with an improved, higher efficiency engine alternator. Intelligent cooling can more easily be applied to vehicles that do not typically carry heavy payloads, so larger vehicles with towing capacity present a challenge, as these vehicles have high cooling fan loads. EPA also included a higher efficiency alternator in this category to improve the cooling system.

EPA considered whether to consider electric oil pump technology for inclusion in their technology assessments. Because it is necessary to operate the oil pump any time the engine is running, electric oil pump technology was judged to have an insignificant effect on efficiency. Therefore, it is not included in this Proposed Determination assessment.

For the cost and effectiveness assumptions EPA is adopting for this Proposed Determination, see Chapter 2.3.

2.2.8.3 Secondary Axle Disconnect: State of Technology

2.2.8.3.1 <u>Background</u>

All-wheel drive (AWD) and four-wheel drive (4WD) vehicles provide improved traction by delivering torque to both the front and rear axles, rather than just one axle. Driving two axles rather than one tends to consumes more energy due to additional friction and rotational inertia. Some of these losses may be reduced by providing a secondary axle disconnect function that disconnects one of the axles when driving conditions do not call for torque to be delivered to both axles.

The terms AWD and 4WD are often used interchangeably. The term AWD has come to be associated with light-duty passenger vehicles that provide variable operation of one or both axles on ordinary roads. The term 4WD is often associated with larger truck-based vehicle platforms that provide for a locked driveline configuration and/or a low range gearing meant primarily for off-road use.

Many 4WD vehicles provide for a single-axle (or two-wheel) drive mode that may be manually selected by the user. In this mode, a primary axle (perhaps the rear) will be powered, while the other axle (known as the secondary axle) is not. Even though the secondary axle is not contributing torque, energy may still be consumed by rotation of its driveline components because they are still connected to the non-driven wheels. This energy loss directly results in increased fuel consumption and CO_2 emissions that could be avoided by disconnecting the secondary axle components under these conditions.

Further, many light-duty AWD systems are designed to variably divide torque between the front and rear axles in normal driving, in order to optimize traction and handling in response to driving conditions. Even when the secondary axle is not delivering torque, it typically remains engaged with the driveline and continues to generate losses that could be avoided by a more advanced disconnect feature. For example, Chrysler has estimated that the secondary axle disconnect in the Jeep Cherokee reduces friction and drag attributable to parasitics of the secondary axle by 80 percent when in disconnect mode.[487] Some of the sources of secondary axle parasitics include lubricant churning, seal friction, bearing friction, and gear train losses.[488,489]

Many part-time 4WD systems, such as those seen in light trucks, use some type of secondary axle disconnect to provide shift-on-the-fly capabilities. In many of these vehicles, particularly light trucks, the rear axle is permanently driven and the front axle is secondary. The secondary axle disconnect is therefore part of the front differential assembly in these vehicles. Light-duty passenger cars that employ AWD may instead permanently power the front wheels while making the rear axle secondary, as currently in production in the Jeep Cherokee 4WD system.

As part of a shift-on-the-fly 4WD system, the secondary axle disconnect serves two basic purposes. First, in two-wheel drive mode, it disengages the secondary axle from the driveline so the wheels do not turn the secondary driveline at road speed, reducing wear and parasitic energy losses. Second, when shifting from two- to four-wheel drive "on the fly" (while moving), the secondary axle disconnect couples the secondary axle to its differential side gear only after the synchronizing mechanism of the transfer case has spun the secondary driveshaft up to the same speed as the primary driveshaft.

4WD systems that have a disconnect typically do not have either manual- or automatic-locking hubs. To isolate the secondary wheels from the rest of the secondary driveline, axle disconnects use a sliding sleeve to connect or disconnect an axle shaft from the differential side gear.

2.2.8.3.2 *Developments in AWD Technology*

Since the FRM, EPA has continued to monitor developments in AWD secondary axle disconnects and their adoption in the light-duty vehicle fleet.

As discussed in the Draft TAR, EPA coordinated with Transport Canada and Environment and Climate Change Canada on a project to characterize AWD systems present in the market today. The primary objectives of this project were to gain an overview of AWD technology in general and to understand the potential effect of advances in these systems on GHG performance in comparison to their 2WD variants. A comprehensive technical characterization of 17 in-production AWD systems has been completed.[489] It includes characterization of system architecture, operating modes, and current usage in the fleet. It also estimated and compared the mass and rotational inertia of AWD components and parts to those of 2WD variants in order to better understand the weight increase associated with AWD. Additionally, the all-wheel-drive components of three AWD vehicles (the 2015 Jeep Cherokee Limited 4x4, 2015 Ford Fusion AWD, and 2015 Volkswagen Tiguan Trendline 4motion) underwent a teardown in order to accurately characterize their mass and rotational inertia and estimate their approximate cost. One of the teardown vehicles, the Jeep Cherokee, includes a secondary axle disconnect, indicating that this technology has begun to appear in light-duty vehicles since the FRM. In 2014, Chrysler Group LLC presented a very positive outlook on the advantages of this system for improving fuel efficiency while retaining a highly competitive off-road capability.[490] This suggests that the addition of secondary axle disconnect systems need not be accompanied by loss of traction and handling capability.

The study reinforced the perception that AWD is rapidly increasing in popularity in the vehicle fleet, with about one-third of all vehicles sold in North America in 2015 having AWD capability. The prevalence of AWD varies significantly between vehicle segments and trim levels. Sedans have the lowest AWD availability, while AWD versions outnumber 2WD versions in the SUV and pickup segments, particularly among the higher trim levels in each segment.

The study identified several areas of potential efficiency improvement for AWD systems. These included system level improvements such as: use of a single shaft Power Transfer Unit (PTU), which can save up to 10kg in mass compared to a two-shaft unit; careful integration into vehicle architecture; downsizing the driveline to further reduce mass while providing sufficient traction in adverse conditions; and use of electric rear axle drive (eRAD). Component level improvements were also identified, including: use of fuel-efficient bearings, low drag seals, improved lubrication strategies, use of high-efficiency lubricants, advanced CV joints, and dry clutch systems. Design improvements such as hypoid offset optimization, bearing preload optimization, use of single-shaft power transfer units (PTUs) and an optimized propshaft gear ratio were also suggested to have potential. Use of weight-reducing metals such as magnesium, and manufacturing improvements such as vacuum die casting and improved hypoid manufacturing were also cited as opportunities. The authors' judgement of the relative potential for AWD efficiency improvements offered by each opportunity are depicted in Figure 2.63.

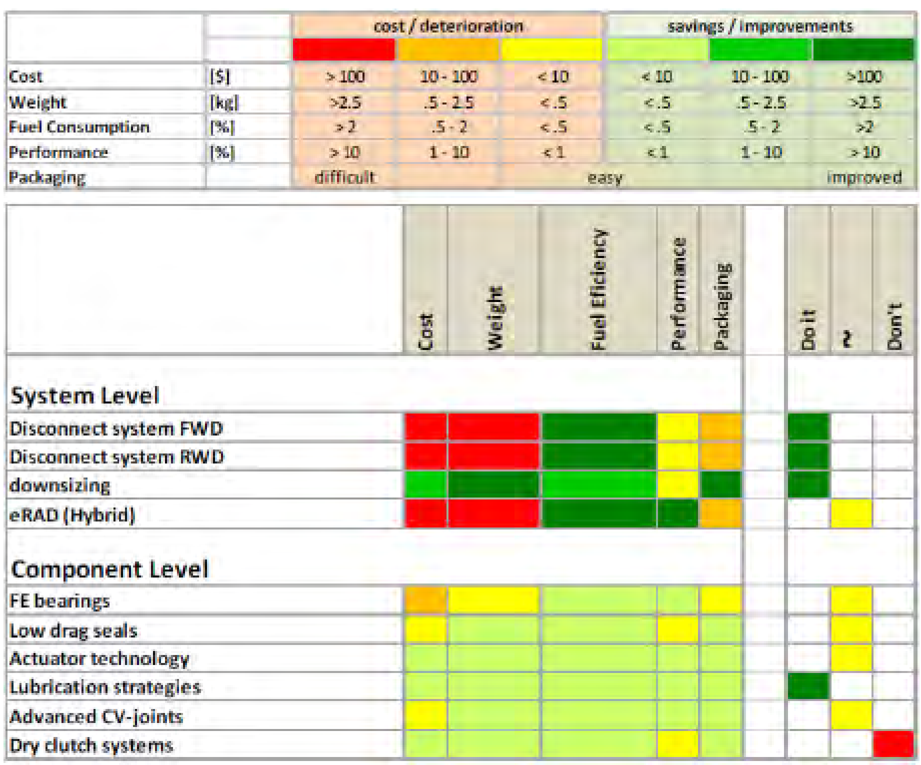


Figure 2.63 Summary of AWD Efficiency Improvement Potentials[489]

Various sources cited in the study suggested that AWD disconnect systems have the ability to lower fuel consumption of AWD vehicles by between 2 percent and 7 percent, significantly higher than the estimates of 1.2 percent to 1.4 percent used in the 2012 FRM. However, it should be noted that a disconnect strategy must balance fuel efficiency with other concerns such as vehicle dynamics, traction and safety requirements, which may act to reduce its actual GHG effectiveness.

The study also identified three primary technological trends taking place in AWD system design, including: actively controlled multi-plate clutches (MPCs), active disconnect systems (ADS), and electric rear axle drives (eRAD). While controlled MPCs appear to be the dominant technology in on-demand systems, ADS is a more recent trend and holds promise for reducing real world fuel consumption. eRAD is the most recent emerging technology with potential for even greater improvements (as seen in the Volvo XC90 Hybrid SUV).

The teardown analysis analyzed three power transfer units (PTUs) and rear drive modules (RDMs) from the Ford Fusion, Jeep Cherokee and VW Tiguan. These were non-destructively disassembled and analyzed with respect to mass, rotational inertia and the presence of specific design features. Figure 2.64 shows the contribution of individual AWD driveline components to the total additional mass of the AWD variant of each vehicle compared to the 2WD variant. Further analysis of rotational inertias of these parts suggested that rotational inertias add very little equivalent mass and therefore probably do not carry a large impact on fuel consumption.

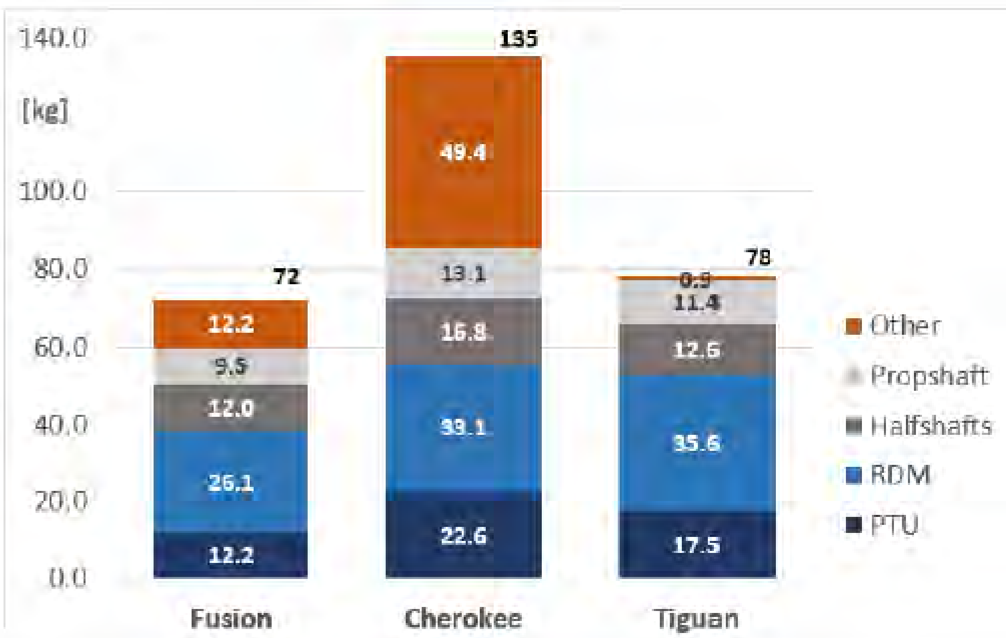


Figure 2.64 Contribution of Individual AWD Driveline Components to Total Additional Vehicle Mass

The study included a high-level cost analysis for these parts, including the mechanical disconnect device and modifications necessary to the torque transfer device (TTD). The total cost of adding secondary axle disconnect to a vehicle was estimated at approximately \$90 to \$100. Although this cost estimate was informally derived based primarily on the experience and expertise of the authors, it compares well to the total cost (TC) figure attributed to 2017 in the FRM analysis, at \$98. The authors noted that the cost for the Jeep Cherokee system would likely be higher because this system was designed to accommodate a planetary low gear, which adds mass and cost not related to the AWD disconnect function.

In addition to the in-production disconnect concepts described in the Transport Canada AWD report, activity continues in the development of innovative secondary axle disconnect concepts. For example, in 2015, Schaeffler presented a novel design for a clutch mechanism for use in AWD disconnect.[491] Suppliers are also designing and marketing modular solutions for integration into existing OEM products.[488] Developments such as these suggest that multiple potential paths will exist for disconnect technology to accompany the increasing growth and popularity of AWD in light-duty vehicles.

In conjunction with the AWD characterization project described above, Transport Canada is also conducting a program of coast down testing, chassis dynamometer testing, and on-road testing of several Canada-specification AWD vehicles at Transport Canada facilities. This portion of the effort was not yet completed at the time of this Proposed Determination.

For the cost and effectiveness assumptions EPA adopted for the Draft TAR analysis, which are retained for the Proposed Determination analysis, see Section 2.3.

2.2.8.4 Low-Drag Brakes: State of Technology

Low or zero drag brakes reduce or eliminate the sliding friction of disc brake pads on rotors when the brakes are not engaged. By allowing the brake pads to pull or be pushed away from the rotating disc either by mechanical or electric methods, the drag on the vehicle is reduced or eliminated.

The reduction of brake drag is a technology that vehicle manufacturers have focused on for many years. The ability to allow the brake disc pads to move away from the rotor and thereby reduce friction is a known technology. This has been historically implemented by designing a caliper and rotor system that allows the piston in the caliper to retract. However, if the pads are allowed to move too far away from the rotor, the first pedal apply made by the vehicle operator can feel spongy and have excessive travel. This can lead to customer dissatisfaction regarding braking performance and pedal feel. For this reason, in conventional hydraulic-only brake systems, manufacturers are limited by how much they can allow the pads to move away from the rotor.

Recent developments in braking systems have allowed suppliers to provide brakes that have the potential for zero drag. In this system the pad is allowed to move away from the rotor in much the same way that is done in today's conventional brake systems, but in a zero drag brake system the pedal feel is separated from the hydraulics by a pedal simulator. The pedal simulator provides a portion of the overall braking feel specifically that of the tactile feel provided to the vehicle operator. The other portion of brake feel is determined by the actual deceleration felt by the vehicle operator. In a properly designed brake system the tactile pedal feel and the associated vehicle deceleration is linear, consistent and predictable over all vehicle operating conditions. This application of a pedal simulator is very similar to the brake systems that have been designed for hybrid and electric vehicles. In hybrid and electric vehicles, some of the primary braking is done through the recuperation of kinetic energy in the drive system. However, the pedal feel and the deceleration that the operator experiences is tuned to provide a braking experience that is equivalent to that of a conventional hydraulic brake system. These "brake-by-wire" systems have highly tuned pedal simulators that feel like typical hydraulic brakes and seamlessly transition to a conventional system as required by conditions. In addition to the pedal simulator, the conventional vacuum-assisted master cylinder in a brake-by-wire system is replaced by a replaced by an electric pump that is able to build brake pressure as indicated by the position of the brake pedal. Because the electric pump is able to build brake pressure faster than most vehicle operators, operators do not experience any deterioration in stopping performance, even under conditions where the brake pads have moved slightly away from the brake rotors. The application of a pedal simulator and brake-by-wire system is new to non-electrified vehicle applications. If the pedal simulator and electric pump are tuned properly, the initial pedal depression, even with the pads moved slightly away from the rotor, can provide the same pedal feel and vehicle deceleration characteristics associated with a conventional brake system.

In addition, to reducing brake drag, the zero drag brake system may also provide ancillary benefits. It could allow for a faster brake apply and greater deceleration than is normally applied by the average vehicle operator. It may also allow manufacturers to tune the braking for different customer preferences within the same vehicle. This means that a manufacturer can provide a "sport" mode which provides greater deceleration with less pedal displacement and a "normal" mode which might be more appropriate for day-to-day driving. These electrically driven systems may also facilitate other brake features such as panic brake assist, automatic braking for crash avoidance and could support future autonomous driving features.

The zero drag brake system that are electrically driven also eliminates the need for a brake booster. This has the potential to save both cost and weight in the overall system. Elimination of the conventional vacuum brake booster could also improve the effectiveness of stop-start systems. Typical stop-start systems need to restart the engine if the brake pedal is cycled because the action drains the booster of stored vacuum. Because the zero drag brake system provides braking assistance electrically, there is no need to supplement lost vacuum during an engine off event.

Finally, many of the engine technologies being considered to improve efficiency reduce pumping losses through reduced throttle. The reduction in throttle could result in supplemental vacuum being required to operate a conventional brake system. This is the situation in many diesel-powered vehicles. Diesel engines run without a throttling and often require supplemental vacuum for brake boosting. By using a zero drag brake system, manufacturers may realize the elimination of brake drag as well as the ancillary benefits described above and avoid the need for a supplemental vacuum pump.

For the specific cost and effectiveness assumptions EPA is adopting for the Proposed Determination assessment, see Chapter 2.3.

2.2.9 Air Conditioning Efficiency and Leakage Credits

Air conditioning (A/C) is a virtually standard automotive accessory, with over 95 percent of new cars and light trucks sold in the United States being equipped with mobile air conditioning (MAC) systems. This high penetration means that A/C systems have the potential to exert a significant influence on the energy consumed by the light duty vehicle fleet, as well as GHG emissions resulting from refrigerant leakage.

The 2012 final rule allowed vehicle manufacturers to generate credits for improved A/C systems toward complying with the CO_2 and fuel consumption fleet-wide average standards. In the EPA program, manufacturers can generate credits for improved performance of both direct emissions (refrigerant leakage) and indirect emissions (tailpipe emissions attributable to the energy consumed by A/C). In both cases, a selection of "menu" credits in grams per mile are available for qualifying technologies, with the magnitude of each credit being estimated based on the expected reduction in CO_2 emissions resulting from the technology. See 40 CFR 86.1868-12. In the NHTSA program, manufacturers are allowed to generate fuel consumption improvement values for purposes of CAFE compliance based on the use of A/C efficiency-improving technologies. However, manufacturers cannot count reductions in A/C leakage toward their CAFE calculations since these improvements do not affect fuel economy.

Since the FRM, many manufacturers have generated and banked credits through this program and continue to do so today. In the FRM, the agencies estimated that significant penetration of A/C technologies would occur to gain these credits, and this was reflected in the stringency of the standards. See e.g. 77 FR at 62805/3.

EPA projected that the 2017-2025 program would lead to significant reductions in GHGs from reduced A/C refrigerant leakage and from industry adoption of lower global warming potential (GWP) refrigerants. Based on additional information that became available for the Draft TAR analysis, as well as changes in the overall regulatory environment affecting the A/C technology developments in the light-duty vehicle industry, the Draft TAR reaffirmed our conclusion that these technologies will continue to expand and play an increasing role in overall vehicle GHG reductions and regulatory compliance. EPA continues to believe this is the case in this Proposed Determination.

2.2.9.1 A/C Efficiency Credits

2.2.9.1.1 *<u>Manufacturer Utilization of A/C Efficiency Credits</u>*

The A/C credit program continues to be an important component of manufacturers' compliance plans, with many manufacturers continuing to take advantage of the program to generate and bank A/C efficiency credits. The importance of the program was reinforced by many of the comments received on the Draft TAR, strongly reaffirming that OEMs continue to consider A/C credits to be an essential component of their compliance paths. For example, the Alliance of Automobile Manufacturers (AAM) commented, "MAC indirect credits are playing a critical role in industry compliance with the light-duty vehicle GHG regulation, achieving emission reductions that would not otherwise have been possible using the previous CAFE regulatory framework."

As summarized in the EPA Manufacturer Performance Reports,[492,493] 17 auto manufacturers included A/C efficiency and/or leakage credits as part of their compliance demonstration in both the 2014 and 2015 model years. In MY2014, these included more than 10 million Megagrams (Mg) of A/C efficiency credits, or about 25 percent of the total net A/C credits reported that year. In MY2015, utilization of A/C efficiency credits increased to more than 12 million Mg, or 37 percent of the total net credits that year. This was equivalent to about 3 grams per mile across both the 2014 and 2015 fleets. Including the 2012 and 2013 model years, A/C efficiency credits have to date totaled over 36.3 million Mg.

The vast majority of A/C efficiency credits were claimed through the A/C credit menu (see 40 CFR 1868-12(a)), which includes several A/C efficiency-improving technologies that were well defined and had been quantified for effectiveness at the time of the 2012 FRM. Some comments on the Draft TAR praised the pre-defined, pre-approved credit menu approach as being highly effective at incentivizing A/C improvements, and cited the A/C credit program as a good example of how real-world GHG benefits can be recognized and credited.

As discussed in the Draft TAR, EPA expects that additional technologies for improving A/C efficiency that are not represented in the menu may continue to emerge. Although not part of the credit menu, these technologies will continue to be eligible for credit on a case-by-case basis under the off-cycle credit program. An off-cycle credit application for this purpose should be supported by results of testing under the AC17 test protocol using an "A to B" comparison, that is, a comparison of substantially similar vehicles in which one has the technology and the other does not. See 40 CFR section 86.1869-12 (c) and (d).

To date, EPA has received one off-cycle credit application for an A/C efficiency technology. In December 2014, General Motors submitted an off-cycle credit application for the Denso SAS A/C compressor with variable crankcase suction valve technology,[494] requesting an off-cycle GHG credit of 1.1 grams CO_2 per mile. EPA evaluated the application and found that the methodologies described therein were sound and appropriate. Therefore, EPA approved the credit application.[495]

AAM commented on the off-cycle approval process as an alternative route to A/C credits, stating, "Automakers request that EPA simplify and standardize the procedures for claiming off-cycle credits for the new MAC technologies that have been developed since the creation of the MAC indirect credit menu." Other comments noted the importance of continuing to incentivize further innovation in A/C efficiency technologies in the future as new technologies emerge that are not in the credit menu, or when manufacturers begin to reach the regulatory caps on menu credits, and suggested that EPA should consider adding new A/C efficiency technologies to the credit menu and/or update the credit values, particularly those that qualify for credits through an off-cycle application or through such an application are approved for more credit than provided in the menu. For example, Toyota commented, "Toyota appreciates the continued incentives for these emerging A/C efficiency technologies, but it remains unclear as to why the agencies have chosen to not support further development of the existing A/C efficiency incentive menu. Toyota's assessment is that the existing menu items are further improved as well, in which case the incentive values for A/C efficiency should be updated along with including new technologies being deployed."

Although these comments were made in the context of the A/C efficiency program, they border on issues that are closely related to the topic of the off-cycle approval process in general. The off-cycle provisions are described in more detail in Chapter 2.2.10, and comments received on this topic are addressed more fully in the Section B.3.4.1 of the Proposed Determination Appendix (Off-Cycle Technology Credits). With regard to the A/C menu specifically, although it is anticipated that new A/C technologies that are not represented in the credit menu may emerge over the time frame of the MY2022-2025 standards, EPA does not plan to add additional items to the credit menu nor to change the values assigned to those that are currently in the menu. EPA acknowledges that the menu of pre-defined and pre-approved technologies has been well received as a way to incentivize A/C improvements. However, EPA continues to feel that expanding the design-based aspect of the program that is represented by the credit menu, either by adding new technologies or updating the credit values, would be inconsistent with the goal of transitioning the program toward a performance basis, as represented by the phase-in of testing requirements as established in the rule. EPA anticipates that the off-cycle program will continue to serve as the primary mechanism for expanding A/C technology credit opportunities.

The 2012 final rule establishes that menu-based credits for A/C efficiency are subject to a regulatory cap. The rule set a cap of 5.7 g/mi for cars and trucks through MY2016, and separate caps of 5.0 g/mi for cars and 7.2g/mi for trucks for later MYs. See 40 CFR 86.1868-12(b)(2). Several commenters asked EPA to reconsider the applicability of the cap to non-menu A/C efficiency technologies claimed through the off-cycle process, and questioned the applicability of this cap on several different grounds. These comments appear to be in response to a passage in the Draft TAR which stated: "Applications for A/C efficiency credits made under the off-cycle credit program rather than the A/C credit program will continue to be subject to the A/C efficiency credit cap" (Draft TAR, p. 5-210). EPA has considered these comments and presents clarification below.

As additional context, the 2012 TSD states (see p. 5-58, 2012 TSD): "...air conditioner efficiency is an off-cycle technology. It is thus appropriate [...] to employ the standard off-cycle credit approval process [to pursue a larger credit than the menu value]. Utilization of bench tests in combination with dynamometer tests and simulations [...] would be an appropriate alternate method of demonstrating and quantifying technology credits *(up to the maximum level of credits allowed for A/C efficiency)* [emphasis added]. A manufacturer can choose this method even for technologies that are not currently included in the menu." This suggests that the concept of placing a limit on total A/C credits, even when some are granted under the off-cycle program, is not entirely new, and that EPA considered the menu cap as being appropriate at the time.

Looking more specifically at the regulations, the regulatory caps specified under 40 CFR 86.1868-12(b)(2) apply to menu-based credits and are not part of the off-cycle regulation (40 CFR 86.1869-12). However, it should be noted that off-cycle credit applications are decided individually on their merits through a process involving public notice and opportunity for comment. The rationale relied upon for approving or denying credit requests may take into account any factors deemed relevant, including such issues as the realization of claimed credits in real world use. Such factors could include the consideration of synergies or interactions among applied technologies, which could potentially be addressed by application of some form of cap or other applicable limit, if warranted. Therefore, applying for A/C efficiency credits through use of the off-cycle provisions under 86.1869-12 should not be seen as a route to unlimited A/C credits.

Going forward, EPA expects to cap total A/C efficiency credits whether granted through 86.1868-12 or 86.1869-12. That is, through our authority in the off-cycle approval process, we are likely to specify that total A/C efficiency credits be capped in an appropriate manner. At this time EPA believes that, unless information pertinent to a specific application causes a different conclusion, the caps specified in 86.1868-12 are appropriate for this purpose. Applicants can present, as part of the analysis supporting their application, evidence supporting the case that a different conclusion should apply to the application in question.

2.2.9.1.2 Eligibility for A/C Efficiency Credits

EPA has established two test procedures for use in determining eligibility for A/C efficiency credits, the Idle Test and the AC17 Test. The Idle Test procedure, which has now been phased out, and the AC17 test procedure are described in more detail in Draft TAR Chapter 5.2.9.1.

For MYs 2014 to 2016, there were three options for qualifying for A/C efficiency credits: 1) running the Idle Test, as described in the MYs 2012-2016 final rule, and demonstrating compliance with the CO_2 and fuel consumption threshold requirements; 2) running the Idle Test and demonstrating compliance with engine displacement adjusted CO_2 and fuel consumption threshold requirements; and 3) running the AC17 Test and reporting the test results.

In preparation for the 2017-2025 NPRM, the agencies recognized that the Idle Test had limitations, and sought to develop a test procedure that could more reliably generate an appropriate credit value based on an “A” to “B” comparison, that is, a comparison of substantially similar vehicles in which the "A" vehicle is a baseline vehicle without the technology, and the "B" vehicle has the technology. The result of this effort was the AC17 Test Procedure, which is based on a transient drive cycle, rather than just idle.

To develop the AC17 test, EPA initiated a study that engaged automotive manufacturers, USCAR, component suppliers, SAE, and CARB. This effort also explored the applicability and appropriateness of a test method or procedure which combines the results of test-bench, modeling/simulation, and chassis dynamometer testing into a quantitative metric for quantifying A/C system (fuel) efficiency. The goal of this exercise was the development of a reliable, accurate, and verifiable assessment and testing method while also minimizing a manufacturer’s testing burden. EPA believes that the AC17 test procedure is more effective than the Idle Test at accurately reflecting the impact that A/C use (and in particular, efficiency-improving components and control strategies) has on tailpipe CO_2 emissions and fuel consumption. For a complete description of the AC17 Test, please refer to the 2017-2025 TSD or the Draft TAR.

The 2017-2025 rule thus provided for a phasing out of the Idle Test in favor of the AC17 Test. For MYs 2017-2019, the AC17 test becomes the exclusive means to demonstrate eligibility for A/C efficiency credits. By reporting test results, manufacturers gain access to the credits on the menu based on the design of their AC system. Then, beginning in MY 2020, the AC17 test will be used not only to demonstrate eligibility for efficiency credits, but also to partially quantify the amount of the credit. If the delta of the A-to-B test is greater than the value in the credit menu, the manufacturer receives the menu value, otherwise the value is scaled.

However, an engineering assessment can still be conducted as an alternative to baseline ("A") testing to build the case for a specific credit value if, for example, a baseline vehicle does not exist on which to base the A-to-B comparison. See 76 FR 74938, 74940. This provision is found in 86.1868-12(g), which describes the testing requirement applicable to MY2020 and later. In part, the provision includes the following two requirements (paraphrased; see 86.1868-12(g) for text):

(1) Performing the AC17 test on a vehicle that incorporates the air conditioning system with the credit-generating technologies (the "B" vehicle).

(2) And, either:

(a) Performing the AC17 test on a vehicle which does not incorporate the credit-generating technologies (the baseline or "A" vehicle), where the tested vehicle must be similar to the vehicle tested under (1) and selected using good engineering judgment. The tested vehicle may be from an earlier design generation; or,

(b) If the manufacturer cannot identify an appropriate vehicle to test under (a), they may submit an engineering analysis that describes why an appropriate vehicle is not available or not appropriate, and includes data and information supporting specific credit values, using good engineering judgment.

Thus the regulation still requires that an AC17 test be performed on the "B" vehicle that contains the technology, but an appropriate engineering analysis may, if approved, provide for credit in lieu of identification and testing of a baseline "A" vehicle.

2.2.9.1.3 *The AC17 Test Procedure*

Throughout the development of the AC17 credit program, EPA has worked closely with the industry on a regular basis, through collaboration with USCAR, the Society of Automotive Engineers (SAE), MAC suppliers, and other stakeholders. This effort was acknowledged in comments on the Draft TAR, where the Alliance of Automobile Manufacturers (AAM) cited "the close dialogue on these issues that EPA has maintained with the industry since the 2004-2006 IMAC SAE Cooperative Research Program and the subsequent early stages of development of the MAC indirect GHG credits."

Prior to the 2012 FRM, EPA collaborated with several OEMs to evaluate the AC17 Test by conducting independent testing on a variety of vehicles and air conditioning technologies. The purpose of this effort was to gain insight regarding the appropriateness of the AC17 Test for verifying the reduction in CO_2 emissions expected from A/C technologies on the efficiency credit menu. Initially, six vehicles were tested, including three pairs of carlines with some element of difference in their air conditioner systems. The results of these tests were discussed in the 2012 TSD, Section 5.1.3.7, beginning on page 5-44. This collaborative effort continued to include a variety of additional vehicles tested by several OEMs at AC17-capable test facilities.[496] This preliminary testing showed that the AC17 test is capable of low test-to-test variability, and is suitable for evaluating the relative efficiency improvement of A/C technologies, when confounding factors are minimized. In cases where comparison of the AC17 results do not directly demonstrate the effectiveness of a technology, the test results can still be useful within an engineering analysis for justifying the test methodology to determine A/C CO_2 credits.

EPA also initiated a round-robin test program between facilities of several USCAR members in an effort to determine the repeatability of the AC17 test among various test facilities and to identify potential sources of variability. A 2011 Ford Explorer was selected for these tests. Four test sites were utilized, located at Ford, GM, Chrysler, and an EPA-contracted facility at Daimler. Each facility had a full environmental chamber capable of fulfilling all requirements of the test. Four tests were run at each facility, after which the vehicle was returned to Ford for confirmation. Each test measured CO_2 emissions with A/C off and A/C on, to capture the difference (delta) in CO_2 emissions, which represents the GHG effect of A/C usage.

Figure 2.65 through Figure 2.67 compares the results of each test at each test site. Although some variability was observed between test sites, consistency within a given site was good, suggesting that the AC17 test procedure is able to capture the difference in CO_2 emissions between A/C on and A/C off.

Several sources of variation were identified by analysis of these results. Variations in solar load may have resulted from variations in sensor location and soak start time. Temperature control was also a potential issue. Although most labs could maintain temperature within the required tolerance of the test procedure, humidity was more difficult to maintain for the long duration of the test. Overcorrecting may occur, but can be improved by optimizing sensor location to better represent ambient conditions. The complexity and length of the test can lead to an increased potential for voided tests, and may require more frequent calibration of the test cell equipment. Although this test program was not fully described in materials accompanying the FRM, many of the issues observed during this testing were addressed in the final form of the rule.

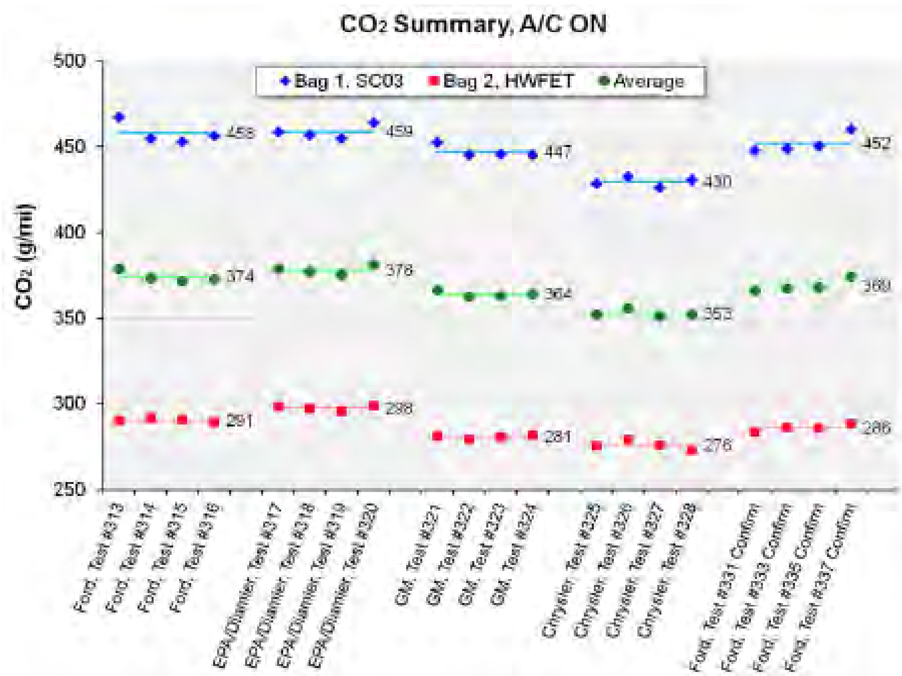


Figure 2.65 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, A/C On

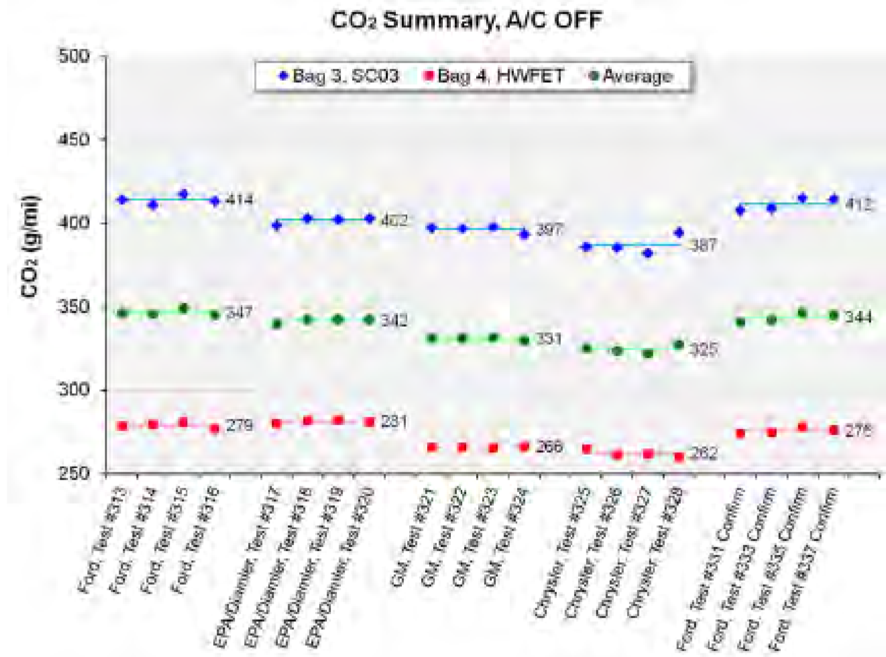


Figure 2.66 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, A/C Off

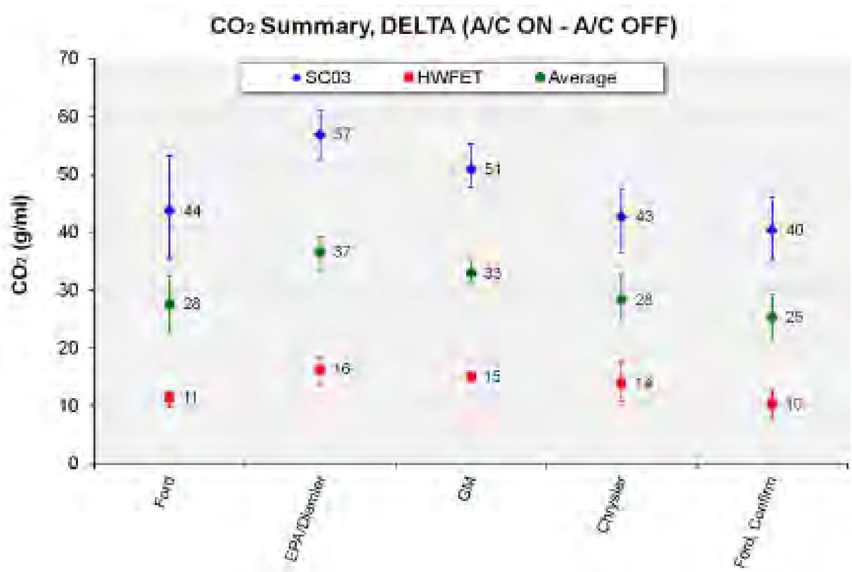


Figure 2.67 Variability of AC17 Round Robin Testing on 2011 Ford Explorer, Delta between A/C on and Off

Although these tests demonstrated that the AC17 test was able to resolve the difference between A/C on and A/C off, they did not address its ability to resolve smaller differences, such as the effect of an individual technology in an A to B test. As the size of an effect diminishes, the difficulty of resolving it against a much larger baseline value becomes more challenging. With the baseline CO_2 g/mi value for most vehicles being in the hundreds, and the effect of a single A/C technology possibly in the low single digits, test-to-test variation must be very small to reliably detect the effect. As the AC17 A-to-B test becomes a requirement beginning in MY2020, this issue is being examined closely by the industry and EPA.

Since the 2012 FRM, USCAR members have conducted an ongoing test program to assess the ability of the AC17 test to resolve the GHG impact of individual A/C efficiency technologies in an A to B test, and thereby function in the role assigned to it in the FRM as a means for quantifying and qualifying for A/C credits. EPA has followed this effort by direct coordination with member OEMs and by participating in meetings of the SAE Interior Climate Control Committee.

As discussed in the Draft TAR, preliminary results of this test program have been encouraging, while providing a robust context for previously identified issues to continue to be assessed. These issues have included:

a) The potential difficulty of obtaining or constructing old-technology vehicles, particularly those from earlier model years, on which to base A-to-B comparisons.
b) Factors such as test-to-test variability and the small magnitude of the effect being measured, which may result in the need for multiple tests to be conducted to yield a statistically reliable result, which would constitute a larger test burden than a single test.
c) Identification of acceptable test procedures and practices for performing bench testing and engineering analysis (as an alternative to performing AC17 testing on a potentially unavailable baseline vehicle).

Members have expressed greater confidence in the ability to conduct AC17-based A-to-B comparisons of software-related technologies (for example, default to recirculated air) than for hardware-based technologies (for example, compressor design changes) because the former can be implemented by relatively simple changes to software in order to represent a baseline "A" vehicle without the technology. A-to-B comparisons of hardware technologies would be more difficult because producing an "A" vehicle without the technology may prove difficult particularly when confounding factors or technologies, or changes in hardware configuration, are present.

In January 2016, EPA received additional comment and analysis from several USCAR members regarding their most recent experience with AC17 testing. In this interaction, many of the issues discussed above were further outlined. Manufacturers have continued to experience a significant number of voided tests and are continuing to work to identify the sources of such events, which are commonly associated with long tests that demand careful environmental control. Test-to-test variation is sometimes seen to exceed the magnitude of the credit value that is the subject of the test. Although averaging of the results of multiple tests has shown some success at establishing a reliable outcome, concerns were expressed about the resulting test burden, due to the length of each test, the control requirements, and the limited availability of the required specialized test cells. The availability of base vehicles without the technology being assessed in an A-to-B comparison was also echoed as a concern. Manufacturers suggested that the use of prior year models may be infeasible when several intervening model years are involved, due to the confounding effect of other technologies introduced to the vehicle during that time. This was expressed as being particularly true for the problem of assessing hardware-based technologies, which may require building of prototype installations that may require additional engineering resources to develop. Within individual test efforts, consistency of results was good in some tests but exhibited inconsistencies in others, of which the manufacturers had not yet achieved a full understanding but continue to study. Issues such as the complexity of modern climate control systems and the presence of confounding factors such as powertrain differences were cited as possible factors.

An application for off-cycle credits submitted by General Motors in December 2014[494] provides an additional source of information on the results of AC17 A-to-B testing, which was used to support the application. GM cited several issues relating to the use of the AC17 test procedure to identify the CO_2 benefit claimed in the application:

a) GM pointed out that the AC17 A-to-B test was enabled by coincidental availability of a valid baseline compressor (a variable compressor without the variable crankcase suction valve technology) in the Holden Commodore and that this compressor coincidentally could be easily bolted into the Cadillac ATS. GM reiterated that this is an uncommon situation and not representative of future expectations.

b) GM stated that this hardware obstacle "prevents ready testing of the benefits of the SAS compressor on other GM models on which it has been implemented."

c) There were some difficulties with torque and pressure measurement which was cited as example of "control issues that may be expected to arise when attempting to do this type of baseline technology testing for hardware on a vehicle that was never actually designed and optimized to use that hardware."

Despite these difficulties, GM found that the AC17 test procedure was able to resolve a 1.3 g/mile CO_2 improvement, which was in good agreement with the 1.1 g/mile suggested by bench testing. However, because test-to-test variability was greater for the AC17 tests than for the bench tests, GM chose to request the 1.1 g/mile shown by the bench tests, which GM regarded as more precise.

As previously described, the final rule provides for pursuing an engineering analysis in place of locating and testing a valid baseline "A" vehicle. EPA has encouraged, and continues to encourage, the use of bench test results and engineering analysis to support applications for A/C efficiency credits in such situations.

Some comments on the Draft TAR expressed uncertainty about the AC17 Test. For example, FCA commented, "A/C efficiency technologies are not showing their full effect on this AC17 test as most technologies provide benefit at different temperatures and humidity conditions in comparison to a standard test conditions. All of these technologies are effective at different levels at different conditions. So there is not one size fits all in this very complex testing approach. Selecting one test that captures benefits of all of these conditions has not been possible."

EPA acknowledges that any single test procedure is unlikely to equally capture the real world effect of every potential technology in every potential use case. This difficulty is well understood among designers of test procedures, and was understood when the AC17 test procedure was developed. While no test is perfect, the AC17 test procedure represents an industry best effort at identifying a test that would greatly improve upon the Idle Test by capturing a much larger range of operating conditions where different technologies are likely to show greater improvement than on the Idle Test. It is our assessment that industry evaluation of the procedure has shown that it achieves this objective.

FCA also commented, "It is a major problem to find a baseline vehicle that is identical to the new vehicle but without the new A/C technology. This alone makes the test unworkable." EPA disagrees that this makes the test unworkable. The regulation describes the baseline vehicle as a "similar" vehicle, selected with good engineering judgment (such that the test comparison is not unduly affected by other differences). Also, as discussed elsewhere, OEMs have expressed confidence in using A-to-B testing to qualify for credits for software-based A/C efficiency technologies. While hardware technologies may pose a greater challenge in locating a sufficiently similar "A" baseline vehicle, the engineering analysis provision under 40 CFR 86.1868-12(g)(2) provides an alternative to locating and performing an AC17 test on such a vehicle. Further, as the USCAR program in general and the GM Denso SAS compressor application specifically have shown, the test is able to resolve small differences in CO_2 effectiveness (1.3 grams in the latter case) when carefully conducted.

Commenters on the Draft TAR also expressed a desire for improvements in the process by which manufacturers without an "A" vehicle could apply under the engineering analysis provision, such as development of standardized engineering analysis and bench testing procedures that could support such applications. For example, Toyota commented, "Toyota requests EPA consider an optional method for validation via an engineering analysis, as is currently being developed by industry." EPA is in fact coordinating with industry on this effort, as described below. Similarly, the Alliance commented, "The future success of the MAC credit program in generating emissions reductions will depend to a large extent on the manner in which it is administered by EPA, especially with respect to making the AC17 A-to-B provisions function smoothly, without becoming a prohibitive obstacle to fully achieving the MAC indirect credits." EPA also has an interest in seeing that the A/C credit program operates as it was designed, and believes that dialogue between EPA and industry stakeholders in the A/C credit program has been in the past, and will continue to be, an effective means toward this goal.

As described in the Draft TAR, in 2016, USCAR members initiated a Cooperative Research Program (CRP) through the Society of Automotive Engineers (SAE) to develop bench testing standards for the four hardware technologies in the credit menu (blower motor control, internal heat exchanger, improved evaporators and condensers, and oil separator). Continuing progress in this effort since the Draft TAR suggests that the availability of these standards may soon resolve much of the uncertainty expressed by the commenters.

The specific standards under development are listed in Table 2.24. The intent of the program is to streamline the process of conducting bench testing and engineering analysis in support of an application for A/C credits under 86.1868-12(g)(2), by creating uniform standards for bench testing and for establishing the expected GHG impact of the technology in a vehicle application. EPA has regularly monitored the development of these standards by coordinating with the CRP as well as participating in the applicable SAE standards development committees. Since completion of the Draft TAR, work has continued on these standards, which appear to be nearing completion.

Table 2.24 Hardware Bench Testing Standards under Development by SAE Cooperative Research Program

Number	Title	Status

J2765	Procedure for Measuring System COP of a Mobile Air Conditioning System on a Test Bench	Published
J3094	Internal Heat Exchanger (IHX) Measurement Standard	Work in Progress
J3109	HVAC PWM Blower Controller Efficiency Measurement	Work in Progress
J3112	A/C Compressor Oil Separator Effectiveness Test Standard	Work in Progress

Commenters also suggested that other aspects of the credit application process should be streamlined. These comments included suggestions such as: (a) that EPA should consider joint applications by OEMs for the same A/C efficiency technology (currently, each OEM has to apply separately); and (b) that EPA should consider allowing suppliers to directly petition for credits and allow the approved credits to be applicable to OEMs that later adopt the technology (currently, suppliers cannot apply independently of OEMs).

In general, the credit application process was designed to evaluate specific implementations of A/C technologies in the context of a specific vehicle or platform. EPA believes that system integration is a major factor in the ability of an identified technology to actually realize real-world fuel-saving and GHG-reducing improvements as part of a mobile A/C system.

It would likely be very challenging for a supplier, for example, to be able to demonstrate (through a hypothetical supplier-sponsored credit application) that a given A/C technology, as represented perhaps by a stock part number, would necessarily always result in the same or similar level of GHG effectiveness regardless of the vehicle on which it is installed. Even for similar classes or sizes of vehicles, it seems likely that specifics of other parts of the system, such as ductwork design, control strategy, and so on would vary significantly among different manufacturers, and the effect of these differences would somehow have to be shown to be inconsequential. Considerations such as these have effectively limited credit applications to OEMs that are proposing a specific vehicle context for application of the technology. At this time, it is likely that an independent supplier application would be seen as incomplete without specific proposed OEM applications of the technology and OEM participation.

Similarly, while the rule does not appear to specifically prohibit multiple OEMs from applying jointly for A/C credits, in order to evaluate such an application if it were presented, the usage of the technology across the participating OEMs would somehow have to be sufficiently similar in each proposed vehicle application to allow the application to be effectively evaluated. EPA experience with evaluating such situations has seen significant variation across vehicle models that integrate the same technologies. It therefore remains unclear whether joint applications would be practical or desirable as a means to streamline the process. Therefore, EPA has not established a process for joint OEM applications.

2.2.9.1.4 Summary

EPA has evaluated and considered the results of AC17 testing presented by stakeholders. These data suggest that the AC17 Test is capable of measuring the difference in CO_2 emissions between A/C on and A/C off, and, when conducted with appropriate attention to detail, is also capable of resolving differences in CO_2 emissions resulting from the addition of A/C efficiency technology. In some cases, test-to-test variability and the small magnitude of the effect to be measured may call for averaging of multiple tests to identify the effect with statistical significance. While the ability to perform full AC17 "A-to-B" testing may in some cases be challenged by the potential unavailability of a valid "A" baseline vehicle, the engineering analysis provision (as described in 40 CFR 86.1868-12(g)(2)) provides an alternative path to credits in these cases.

EPA believes that the bench testing standards being developed by the SAE CRP are an important example of how continued collaboration and dialogue among stakeholders and EPA can facilitate the earning of A/C credits through existing pathways. To this end, EPA is considering the possibility of issuing a guidance letter outlining best practices for applying the SAE standards to an engineering analysis supporting an application for credits as provided in 86.1868-12(g)(2)(ii).

EPA has considered the comments received on the A/C efficiency credit system and the AC17 test procedure, and has also considered what has been learned through the USCAR program and the SAE CRP effort. It is clear that the A/C credit system has been effective at incentivizing technologies that provide real-world GHG-reducing benefits. As the program transitions, as scheduled, to an increasingly performance-based format that includes a requirement for AC17 testing, continued collaboration and dialogue between EPA and the industry has been an effective path toward identifying and developing practical solutions to the issues described above. EPA therefore believes that the existing structure of the A/C credit program will not prevent manufacturers from continuing to qualify for and earn A/C efficiency credits sufficient to provide the contribution to manufacturer compliance paths that manufacturers anticipate.

2.2.9.2 A/C Leakage Reduction and Alternative Refrigerant Substitution

2.2.9.2.1 Leakage

As we observed in the Draft TAR, manufacturers have developed a number of technologies for reducing the leakage of refrigerant to the atmosphere. These include fittings, seals, heat exchanger/compressor designs, and hoses. Vehicle manufacturers consider low-leak technologies to be among the most cost-effective approaches to improving overall vehicle GHG emission performance.

Table 2.25 shows two metrics of the continued industry-wide progress toward durable, low-leak systems. One trend is the annual increase in the generation of leakage credits already apparent in the early years of the program as manufacturers have taken advantage of leakage-reduction incentives. More on this trend, as well as a breakdown of leakage credits by manufacturer, are found in EPA's *Manufacturer Performance Report for the 2015 Model Year*.[497] Specifically, 13 manufacturers reported A/C leakage credits in the 2015 model year, amounting to more than 20.3 million Megagrams (Mg) of credits. This equates to GHG reductions of about 6 grams per mile across the 2015 vehicle fleet. The table also shows the trend toward more leak-proof A/C systems in terms of refrigerant leakage scores across the industry, as indicated by the average industry-wide A/C system leakage scores that the State of Minnesota requires automakers to report (using the SAE J-2727 method).[498]

Table 2.25 Trends in Fleet-wide Mobile Air Conditioner Leakage Credits and Average Leakage Rates

	2009	2010	2011	2012	2013	2014	2015
Credits: (Million Megagrams/Grams/mi)	6.2/*	8.3/*	8.9/*	11.1/4.0	13.2/4.2	16.6/5.1	20.3/5.8
MN SAE J-2727 Leakage Rate (g/yr)	15.1	14.7	14.6	14.5	13.9	13.0	12.1

* Fleet-wide leakage credits in terms of grams/mi are not available prior to MY 2012 due to the optional nature of the leakage credit program in the earlier years.

2.2.9.2.2 Low-GWP Refrigerants

In support of the LD GHG rules, EPA projected that the industry would fully transition to lower-GWP refrigerants between Model Year (MY) 2017 and MY2021, beginning with 20 percent transition in MY2017, to be followed by a 20 percent increase in substitution in each subsequent model year, completing the transition by MY2021 (77 FR 62779, 62778, 62805). Put another way, the stringency of the MY2021 and later light duty GHG standards is predicated on 100 percent substitution of refrigerants with lower GWPs than HFC-134a. On July 20, 2015, EPA published a final rule under the Significant New Alternatives Policy (SNAP) program that changes the listing status of HFC–134a to unacceptable for use in A/C systems of newly-manufactured LD motor vehicles beginning in MY2021, except where permitted for some export vehicles through MY2025 (80 FR 42870).[WW] EPA's decision to take this action was based on the availability of other substitutes that pose less overall risk to human health and the environment, when used in accordance with required use conditions. Thus all new LD vehicles sold in the United States will have transitioned to an alternative, lower-GWP refrigerant by MY2021.

The July 20, 2015 SNAP final rule has no effect on how manufacturers may choose to generate and use air conditioning leakage credits under the LD GHG standards. As stated in that final rule," [n]othing in this final rule changes the regulations establishing the availability of air conditioning refrigerant credits under the GHG standards for MY2017-2025, found at 40 CFR 86.1865-12 and 1867-12. The stringency of the standards remains unchanged…. [M]anufacturers may still generate and utilize credits for substitution of HFC-134a through the 2025 model year." EPA also there noted that the SNAP rule was not in conflict with the Supplemental Notice of Intent (76 FR 48758, August 9, 2011) that described plans for EPA and NHTSA's joint proposal for model years 2017-2025, since EPA's GHG program continues to provide the level of air conditioning credits available to manufacturers as specified in that Notice: "[T]he Supplemental Notice of Intent states that '(m)anufacturers will be able to earn credits for improvements in air conditioning . . . systems, both for efficiency improvements . . . and for leakage or alternative, lower-GWP refrigerants used (reduces [HFC] emissions).' 76 FR at 48761. These credits remain available under the light-duty program at the level specified in the Supplemental Notice of Intent, and using the same demonstration mechanisms set forth in that Notice." 80 FR 42896-97.

EPA has listed three lower-GWP refrigerants as acceptable, subject to use conditions (listed at 40 CFR Part 82, Subpart G), for use in newly-manufactured LD vehicles: HFO-1234yf, HFC-152a, and carbon dioxide (CO_2 or R-744). Manufacturers are currently manufacturing LD vehicles using HFO-1234yf, and they are actively developing LD vehicles using CO_2[499] and considering the use of HFC-152a in a secondary loop A/C system.[500]

EPA expects that vehicle manufacturers will use HFO-1234yf for the vast majority of vehicles. As discussed in the EPA Manufacturer Performance Report referenced above, the use

[WW] HFC-134a will remain listed as acceptable subject to narrowed use limits through MY2025 for use in newly manufactured LD vehicles destined for export, where reasonable efforts have been made to ascertain that other alternatives are not technically feasible because of lack of infrastructure for servicing with alternative refrigerants in the destination country. (40 CFR Part 82, Subpart G, Appendix B.

of HFO-1234yf expanded considerably in recent years, from two manufacturers and 42,384 vehicles in the 2013 model year, to five manufacturers and 1,762,985 vehicles in the 2015 model year, over 10 percent of 2015 model year vehicles are using this refrigerant. This trend reinforces EPA's projection that the industry will have transitioned 20 percent of the fleet by MY2017, as discussed above. Fiat Chrysler accounted for more than 95 percent of these vehicles, introducing HFO-1234yf in over 75 percent of their models. Jaguar Land Rover achieved the greatest penetration within their fleet, using HFO-1234yf in almost 90 percent of Jaguar Land Rover vehicles produced in the 2015 model year.

Finally, regarding supply of alternative refrigerants, the July 2015 SNAP final rule stated that EPA "considered the supply of the alternative refrigerants in determining when alternatives would be available. At the time the light-duty GHG rule was promulgated, there was a concern about the potential supply of HFO-1234yf. Some commenters indicated that supply is still a concern, while others, including two producers of HFO-1234yf, commented that there will be sufficient supply. Moreover, some automotive manufacturers are developing systems that can safely use other substitutes, including CO_2, for which there is not a supply concern for the refrigerant. If some global light-duty motor vehicle manufacturers use CO_2 or another acceptable alternative, additional volumes of HFO-1234yf that would have been used by those manufacturers will then become available. Based on all of the information before the agency, EPA believes production plans for the refrigerants are in place to make available sufficient supply no later than MY2021 to meet current and projected demand domestically as well as abroad, including, but not limited to, the EU" (80 FR 42891; July 20, 2015). In their public comments on the Draft TAR, Honeywell, a supplier of HFO-1234yf, said, "[w]e are in agreement with EPA that by 2021 there will be sufficient capacity of HF0-1234yf around the world to serve the global demand for this refrigerant…. Honeywell and its key suppliers are investing approximately US$300 million to increase global production capacity for HFO-1234yf."

2.2.9.2.3 Conclusions

As described in this section, there is strong evidence that auto manufacturers are continuing to improve the leak-tightness of their A/C systems. In addition, many manufacturers are transitioning to the use of low-GWP alternative refrigerants in a number of vehicle models. We believe that the current trends among automakers toward the use of alternative refrigerants to comply with the LD vehicle GHG standards, EPA's change in listing status of HFC-134a to "unacceptable" by MY2021, and the parallel increase in the supply of the leading alternative refrigerant ensure that our earlier projections that a complete transition to alternative refrigerants by MY2021 will in fact become reality.

The MY2017-2025 LD GHG rule also encourages manufacturers to continue to use low-leakage technologies even when using alternative refrigerants. Although some leakage may still occasionally occur, the low GWPs of the new refrigerants, as compared to that of HFC-134a, considerably reduce concerns about refrigerant leakage from a climate perspective.

2.2.10 Off-cycle Technology Credits

2.2.10.1 Off-cycle Credits Program

2.2.10.1.1 Off-cycle Credits Program Overview

EPA provides an opportunity for credits for off-cycle technologies. EPA initially included off-cycle technology credits in the MY2012-2016 rule and revised the program in the MY2017-2025 rule.[501] "Off-cycle" emission reductions can be achieved by employing off-cycle technologies that result in real-world benefits, but where that benefit is not adequately captured on the test procedures used by manufacturers to demonstrate compliance with and fuel economy emission standards.

The intent of the off-cycle provisions is to provide an incentive for CO_2 reducing off-cycle technologies that would otherwise not be developed because they do not offer a significant 2-cycle benefit. EPA limited the eligibility to technologies whose benefits are not adequately captured on the 2-cycle test. The preamble to the final rule provides a detailed discussion of eligibility for off-cycle credits.[502] Technologies that are integral or inherent to the basic vehicle design including engine, transmission, mass reduction, passive aerodynamics, and base tires are not eligible. Any technology that was included in the agencies' standard-setting analysis also may not generate off-cycle credits (with the exception of active aerodynamics and engine stop-start systems).[503] EPA established this approach believing that the use of 2-cycle technologies would be driven by the standards and no additional credits would be necessary or appropriate. This approach also limits the program to off-cycle technologies that could be clearly identified as add-on technologies more conducive to A-to-B testing that would be able to demonstrate the benefits of the technology. Further limitations are placed on technologies that might otherwise be incentivized through federal safety regulations.[504]

There are three pathways by which a manufacturer may generate off-cycle CO_2 credits. The first is a predetermined list of credit values for specific off-cycle technologies that may be used beginning in MY2014.[505] This pathway allows manufacturers to use conservative credit values established in the MY2017-2025 final rule for a wide range of technologies, with minimal data submittal or testing requirements. In cases where additional laboratory testing can demonstrate emission benefits, a second pathway allows manufacturers to use a broader array of emission tests (known as "5-cycle" testing because the methodology uses five different testing procedures) to demonstrate and justify off-cycle CO_2 credits.[506] The additional emission tests allow emission benefits to be demonstrated over some elements of real-world driving not captured by the GHG compliance tests, including high speeds, rapid accelerations, and cold temperatures. Credits determined according to this methodology do not undergo additional public review. The third and last pathway allows manufacturers to seek EPA approval to use an alternative methodology for determining the off-cycle CO_2 credits.[507] This option is only available if the benefit of the technology cannot be adequately demonstrated using the 5-cycle methodology. Manufacturers may also use this option for model years prior to 2014 to demonstrate off-cycle CO_2 reductions for technologies that are on the predetermined list, or to demonstrate reductions that exceed those available via use of the predetermined list. The manufacturer must also demonstrate that the off-cycle technology is effective for the full useful life of the vehicle. Unless the manufacturer demonstrates that the technology is not subject to in-use deterioration, the manufacturer must account for the deterioration in their analysis.

The pre-defined list of technologies and associated car and light truck credits is shown in the tables below.[508] The regulations include a definition of each technology that the technology must meet in order to be eligible for the menu credit.[509] Manufacturers are not required to submit any other emissions data or information beyond meeting the definition and useful life requirements to use the pre-defined credit value. Credits based on the pre-defined list are subject to an annual manufacturer fleet-wide cap of 10 g/mile. Due to expected synergistic effects of the thermal technologies, the credits from the group of thermal control technologies are subject to a per vehicle cap of 3.0 g/mi for cars and 4.3 g/mi for trucks.

Table 2.26 Off-cycle Menu Technologies and CO_2 Credits for Cars and Light Trucks

Technology	Credit for Cars (g/mi)	Credit for Light Trucks (g/mi)
	g/mi	g/mi
High Efficiency Exterior Lighting (at 100W)	1.0	1.0
Waste Heat Recovery (at 100W; scalable)	0.7	0.7
Solar Roof Panels (for 75 W, battery charging only)	3.3	3.3
Solar Roof Panels (for 75 W, active cabin ventilation plus battery charging)	2.5	2.5
Active Aerodynamic Improvements (scalable)	0.6	1.0
Engine Idle Start-Stop w/ heater circulation system	2.5	4.4
Engine Idle Start-Stop without/ heater circulation system	1.5	2.9
Active Transmission Warm-Up	1.5	3.2
Active Engine Warm-Up	1.5	3.2
Solar/Thermal Control	Up to 3.0	Up to 4.3

Table 2.27 Off-cycle Menu Technologies and CO_2 Credits for Solar/Thermal Control Technologies for Cars and Light Trucks

Thermal Control Technology	Credit (g/mi)	
	Car	Truck
Glass or Glazing	Up to 2.9	Up to 3.9
Active Seat Ventilation	1.0	1.3
Solar Reflective Paint	0.4	0.5
Passive Cabin Ventilation	1.7	2.3
Active Cabin Ventilation	2.1	2.8

The two other pathways available to generate off-cycle credits require additional data. The 5-cycle testing pathway requires 5-cycle testing with and without the off-cycle technology to determine the off-cycle benefit of the technology. The final pathway, often referred to as the public process includes a public comment period and is available for technologies that cannot be demonstrated on the 5-cycle test. Manufacturers must develop a methodology for demonstrating the benefit of the off-cycle technology and the methodology is made available for public comment prior to an EPA determination whether or not to allow the use of the methodology to generate credits. The data needed for this demonstration may be extensive, especially in cases where the effectiveness of the technology is dependent on driver response or interaction with the technology. As discussed below, all three methods have been used successfully by manufacturers to generate off-cycle credits.

2.2.10.2 Use of Off-cycle Technologies to Date

Since the Draft TAR, EPA released the MY 2015 GHG Manufacturer Performance Report (or "compliance report"). The MY 2015 compliance report shows that manufacturers are continuing to introduce a wide array of off-cycle technologies to generate off-cycle GHG credits using the pre-defined menu.[510] For the fleet as a whole, off-cycle credits accounted for almost 3 g/mile of credits in MY 2015 compared to 2.3 g/mile of credits in MY 2014. Table 2.28 below shows the percent of each manufacturers' production volume using each of the menu technologies reported to EPA for MY2015 by the manufacturer. Table 2.29 shows the g/mile benefit that each manufacturer reported across its fleet from each off-cycle technology. Like the preceding table, Table 2.29 provides the mix of technologies used in MY2015 across the manufacturers and the extent to which each technology benefits each manufacturer's fleet.

Table 2.28 Percent of 2015 Model Year Vehicle Production Volume with Credits from the Menu, by Manufacturer & Technology (%)

Manufacturer	Active Aerodynamics		Thermal Control Technologies				Engine & Transmission Warmup			Other		
	Grill shutters	Ride height adjustment	Passive cabin ventilation	Active cabin ventilation	Active seat ventilation	Glass or glazing	Solar reflective surface coating	Active engine warmup	Active transmission warmup	Engine idle stop-start	High efficiency exterior lights	Solar panel(s)
BMW	0.0	0.0	0.0	91.0	7.5	0.3	0.0	74.4	0.0	0.0	96.9	0.0
Fiat Chrysler	29.0	3.0	95.0	0.0	5.9	97.4	1.6	55.2	10.5	5.2	66.5	0.0
Ford	60.0	0.0	100.0	0.0	23.5	0.0	0.0	50.1	26.1	9.3	76.8	0.0
GM	9.7	0.0	0.0	0.0	16.5	99.5	38.6	14.4	0.0	8.8	40.0	0.0
Honda	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	72.2	1.5	57.8	0.0
Hyundai	4.9	0.0	0.0	0.0	18.3	89.0	0.0	0.0	52.6	2.7	22.3	0.0
Jaguar Land Rover	0.0	0.0	0.0	0.0	50.7	99.0	0.0	0.0	0.0	97.6	100.0	0.0
Kia	2.2	0.0	0.0	0.0	19.5	99.7	0.0	0.0	16.5	1.9	52.7	0.0
Nissan	9.3	0.0	0.0	0.0	3.3	0.0	15.8	20.8	64.9	0.1	47.2	0.1
Subaru	32.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0
Toyota	0.0	0.2	0.0	0.0	23.5	90.5	30.2	9.2	49.8	11.4	56.2	0.0
Fleet Total	14.6	0.4	23.5	2.3	12.2	51.9	13.2	20.7	28.2	5.8	49.1	0.0

Table 2.29 Off-Cycle Technology Credits from the Menu, by Manufacturer and Technology for MY 2015 (g/mi)

Manufacturer	Active Aerodynamics		Thermal Control Technologies				Engine & Transmission Warmup			Other			
	Grill shutters	Ride height adjustment	Passive cabin ventilation	Active cabin ventilation	Active seat ventilation	Glass or glazing	Solar reflective surface coating	Active engine warmup	Active transmission warmup	Engine idle stop-start	High efficiency exterior lights	Solar panel(s)	Total
BMW	-	-	-	2.1	0.1	0.0	-	1.5	-	-	0.6	-	4.2
Fiat Chrysler	0.2	0.0	1.9	-	0.0	1.6	0.0	1.6	0.4	0.2	0.2	-	6.1
Ford	0.7	-	2.0	-	0.3	-	-	1.2	0.7	0.4	0.3	-	5.6
GM	0.0	-	-	-	0.2	1.4	0.1	0.2	-	0.1	0.2	-	3.0
Honda	-	-	-	-	0.0	-	-	-	1.4	0.0	0.1	-	1.5
Hyundai	0.0	-	-	-	0.2	0.4	-	-	0.8	-	0.0	-	1.5
Jaguar Land Rover	-	-	-	-	0.6	1.2	-	-	-	2.6	0.5	-	4.9

Kia	0.0	-	-	-	0.2	0.6	-	-	0.2	0.0	0.1	-	1.2
Nissan	0.1	-	-	-	0.0	-	0.1	0.4	1.3	0.0	0.1	0.0	2.0
Subaru	0.1	-	-	-	-	-	-	-	-	-	0.0	-	0.2
Toyota	-	0.0	-	-	0.3	0.7	0.1	0.1	0.9	0.2	0.2	-	2.5
Fleet Total	**0.1**	**0.0**	**0.5**	**0.1**	**0.1**	**0.6**	**0.1**	**0.5**	**0.6**	**0.1**	**0.2**	**0.0**	**2.8**
0.0" indicates that the manufacturer did implement that technology, but that the overall penetration rate was not high enough to round to 0.1 grams/mile, whereas a dash indicates no use of a given technology by a manufacturer.													

The credits shown above are based on the pre-defined credit list. Thus far, GM is the only manufacturer to have been granted off-cycle credits based on 5-cycle testing. These credits are for an off-cycle technology used on certain GM gasoline-electric hybrid vehicles. The technology is an auxiliary electric pump, which keeps engine coolant circulating in cold weather while the vehicle is stopped and the engine is off, thus allowing the engine stop-start system to be active more frequently in cold weather.

The third pathway allows manufacturers to seek approval to use an alternative methodology for determining the off-cycle technology CO_2 credits. Several manufacturers have petitioned for and been granted use of an alternative methodology for generating credits. In the fall of 2013, Mercedes requested off-cycle credits for the following off-cycle technologies in use or planned for implementation in the 2012-2016 model years: stop-start systems, high-efficiency lighting, infrared glass glazing, and active seat ventilation. EPA approved methodologies for Mercedes to determine these off-cycle credits in September of 2014.[511] Subsequently, FCA, Ford, and GM requested off-cycle credits under this pathway. FCA and Ford submitted applications for off-cycle credits from high efficiency exterior lighting, solar reflective glass/glazing, solar reflective paint, and active seat ventilation. Ford's application also demonstrated off-cycle benefits from active aerodynamic improvements (grill shutters), active transmission warm-up, active engine warm-up technologies, and engine idle stop-start. GM's application described the real-world benefits of an air conditioning compressor with variable crankcase suction valve technology. EPA approved the credits for FCA, Ford, and GM in September of 2015.[512] FCA reported 2,599,923 Megagrams of off-cycle credits to EPA for the 2009-2013 model years. In the 2015 model year, GM reported earning 348,102 Mg of credits from the Denso A/C compressor.

More recently, EPA published a notice in the Federal Register on September 2, 2016, requesting comments on methodologies for off-cycle credits submitted by BMW, Ford, GM, and VW.[513] The comment period closed on October 3, 2016, and EPA is currently evaluating comments and drafting a decision document. If approved, these credits would appear in a future edition of the compliance report to the extent that manufacturers claim them.

As discussed above, the vast majority of credits in MY2015 were generated using the pre-defined menu. Even though the program has been in place for only a few model years, the level of credits reported has already been significant for some manufacturers. FCA and Ford generated the most off-cycle credits on a fleet-wide basis, reporting credits equivalent to about 6.1x g/mile and 5.6x g/mile, respectively.[XX] Several other manufacturers report fleet-wide credits in the range of about 1 to 5 g/mile. The fleet total across all manufacturers was equivalent to about 3 g/mile for MY2015. EPA expects that as manufacturers continue to

[XX] The credits are reported to EPA by manufacturers in Megagrams. EPA has estimated a g/mile equivalent.

expand their use of off-cycle technologies, the fleet-wide impacts will continue to grow with some manufacturers potentially approaching the 10 g/mile fleet-wide cap applicable to credits that are based on the pre-defined list.

Please see Proposed Determination document appendix section B.3.4.1 for further discussion of off-cycle credits including comments received on the Draft TAR.

2.3 GHG Technology Assessment

2.3.1 Fundamental Assumptions

2.3.1.1 Technology Time Frame and Measurement Scale for Effectiveness and Cost

The effectiveness and cost associated with applying a technology will depend on the starting technologies from which improvements are measured. For example, two vehicles that start with different technologies will likely have different cost and effectiveness associated with adopting the same combination of technologies. The importance of clearly specifying the point of comparison for cost and effectiveness estimates was highlighted in the 2015 NAS committee's finding "that understanding the base or null vehicle, the order of technology application, and the interactions among technologies is critical for assessing the costs and effectiveness for meeting the standards."

As long as the point of comparison is maintained consistently throughout the analysis for both the baseline and future fleets, the decision of where to place an origin along the scale of cost and effectiveness is inconsequential. For EPA's technology assessment, the origin is defined to coincide with a "null technology package," which represents a technology floor such that all technology packages considered in this assessment will have equal or greater effectiveness, consistent with the approaches used in the 2012 FRM and Draft TAR. While other choices would have been equally valid, this definition of a "null package" has the practical benefit of avoiding technology packages with negative effectiveness values, while also allowing for a direct comparison of effectiveness assumptions with the FRM and Draft TAR.

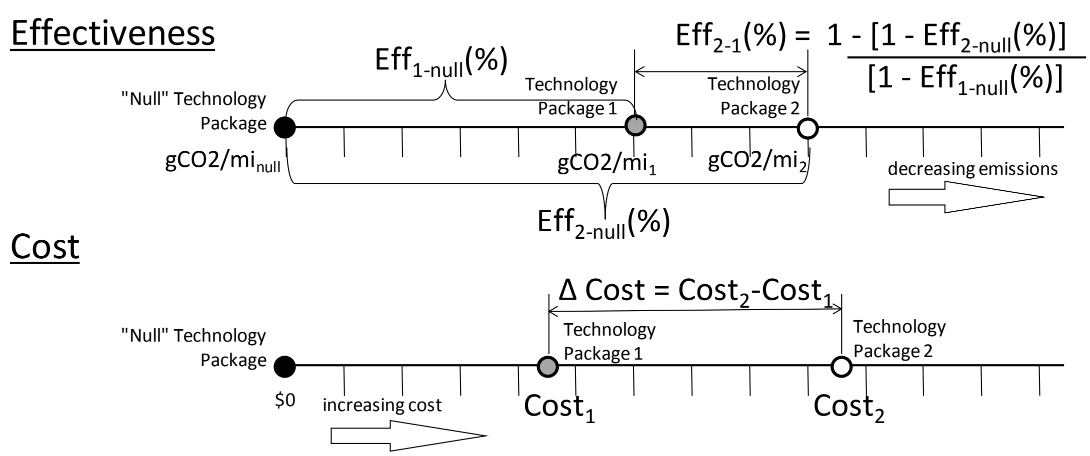


Figure 2.68 The "Null Technology Package" and Measurement Scale for Cost and Effectiveness

When technologies can be specifically identified for individual vehicle models, it is possible to estimate cost and effectiveness values specifically for those models. To the extent possible with the available information, EPA has attempted to consider this. This is the case, for example, with mass reduction and improvements in aerodynamics and tire rolling resistance, where for this assessment EPA has uniquely characterized the various levels of those technologies for individual models based on available road load data. For other technologies, the information that is broadly available across the entire fleet is not detailed enough to distinguish differences that arise to different implementations of the technologies.

The Global Automakers, Ford and other stakeholders commented on several topics with regard to technology adoption that can be considered as universal comments. These comments stated that EPA had not properly considered the amount of lead time required for technology development and adoption, the impact of global vehicle manufacturing and its effect on component availability, and platform sharing. With respect to lead time, EPA believes that vehicle manufacturers do have adequate lead time to meet the 2022~2025 MY standards. The technologies considered in the Proposed Determination are either currently in production or will be commercially produced in the next several years. In addition, the standards that are being reaffirmed in the Proposed Determination were set in 2012 calendar year, which provided vehicle manufacturers 13 years of lead time. For every manufacturer this amount of lead time represents multiple vehicle redesign cycles that provide opportunities for adopting mass reduction, aerodynamic improvements, new powertrains, and lower rolling resistance tires. In addition, this amount of lead time also has provided the opportunity for vehicle manufacturers to consider and manage the effects of the standards on their global manufacturing and on platform sharing. Finally, in addition to the GHG standards required by the United States, most countries around the world are adopting standards that are more stringent. All of these standards in unison are driving vehicle manufacturers to produce increasingly efficient vehicles for all world markets.

2.3.1.2 Performance Assumptions

When determining cost and effectiveness values for specific technologies, it is important to compare the technologies on a consistent basis, so that the relative cost-effectiveness of the technologies can be fairly compared. The National Academy of Sciences states in their 2011 report: "Estimating the cost of decreasing fuel consumption requires one to carefully specify a basis for comparison. The committee considers that to the extent possible, fuel consumption cost comparisons should be made at equivalent acceleration performance and equivalent vehicle size."[514] This is because "objective comparisons of the cost-effectiveness of different technologies for reducing [fuel consumption] can be made only when vehicle performance remains equivalent."[515] The National Academy of Sciences engaged the University of Michigan for their 2015 report to perform a set full vehicle simulations. As a ground rule, "Each engine configuration was modeled to maintain, as closely as possible, the torque curve of the baseline naturally aspirated engine so that equal performance, as measured by 0-60 mph acceleration time, would be maintained."[516] The EPA agrees that it is appropriate to objectively compare technology costs and effectiveness, that maintaining constant vehicle performance is the appropriate way to achieve that goal, and that the NAS recommendation of "equivalent acceleration performance" is appropriate. Thus, the costs and effectiveness presented in this document are based on the application of technology packages while holding the underlying acceleration performance constant.

In most cases, equivalent acceleration performance is achieved by "engine downsizing": reducing the size (and thus the output power/torque) of the engine in advanced vehicle packages until a series of performance metrics are maintained within a reasonable range of the target value similar to the methodology used in the FRM and Draft TAR. A smaller engine will typically be more efficient at the same speed and torque than a larger engine (as pumping losses are reduced), so this methodology properly accounts for effectiveness that could be used for acceleration performance as fuel consumption reduction, thus allowing an objective and fair comparison of technologies. Our process maintains performance neutrality. As recommended by the NAS (2011, 2015), EPA is working under the premise that technology cost assessments should be made under the assumption of equivalent performance. As such, the ALPHA modeling runs generate effectiveness values which maintain a set of acceleration metrics within a reasonable window.

EPA recognizes that manufacturers have many vehicle attribute and manufacturing constraints. Manufacturers will make many product planning decisions and the final products will have engine displacement which represent the OEM's decision in its product plans. As a modeling convenience, when calculating effectiveness, EPA assumes the appropriate component sizing to maintain performance. Even if our model produces a greater variation in technology packages than exists today (for example, by producing two levels of tire rolling resistance on a vehicle platform compared to just one today), this does not require that manufacturers actually produce a greater variety of component sizes than exist currently in order for our overall results to be valid. In actual vehicle design, manufacturers will design discretely sized components, and for each vehicle choose the available size closest to the optimal for the given load and performance requirements. For example, in some cases, the chosen engine will be slightly smaller than optimal (and thus lower fuel consumption), and in some cases the chosen engine will be slightly larger than optimal (and thus higher fuel consumption). The same assumption is applied to drivetrain, suspension, chassis components, etc. For example, brake rotors may be sized in 15mm diameter increments, and manufacturers will apply the size that most closely matches the performance and load requirements of that application. Just as the manufacturers are doing today, EPA expects that they will average these product decisions across their entire fleet. In our analysis, on average, the actual fleet of vehicles will use the appropriate component size, and CO_2 emissions and performance of the fleet will average out, with no significant net change compared to the original analysis with unconstrained component sizes.

In gathering information on technology effectiveness, EPA relied on a wide variety of sources. These sources provided information on the costs and effectiveness of various technologies, but not all comparisons were done on a rigorously performance-neutral basis. Thus, it was often necessary to recalculate the effectiveness of a particular technology when the original comparison was done without the assumption of equivalent performance. For example, the 2011 NAS report, in discussing continuously variable valve lift (CVVL)[517] cites Energy and Environmental Analysis, Inc.,[518] which "estimates a 6.5 to 8.3 percent reduction in fuel consumption at constant engine size and 8.1 to 10.1 percent with an engine downsize to maintain constant performance."

When EPA modeled effectiveness of specific technologies of their combinations, it was careful to maintain a minimum deviation of acceleration performance from the baseline vehicle. As the NAS notes, "truly equal performance involves nearly equal values for a large number of measures such as acceleration (e.g., 0-60 mph, 30-45 mph, 40-70 mph, etc.), launch (e.g., 0-30 mph), grade-ability (steepness of slopes that can be climbed without transmission downshifting), maximum towing capability, and others."[519] However, they furthermore state that "in the usage herein, equal performance means 0-60 mph times within 5 percent. This measure was chosen because it is generally available for all vehicles."

In vehicle simulation modeling in ALPHA performed since the FRM, EPA investigated using additional performance criteria to define an overall performance metric. EPA chose four acceleration performance metrics: 0-60 time, ¼ mile time, 30-50 passing time, and 50-70 passing time. These metrics were chosen to give a reasonably broad set of acceleration metrics that would be sensitive enough to represent true acceleration performance, but not so sensitive that minor changes in vehicle parameters would significantly change the final metric. For each vehicle class, a baseline configuration was chosen, the vehicle package was run over the performance cycle, and the times for each performance metric were extracted. These four metrics were summed for the baseline vehicle. For each vehicle technology package based on the same vehicle class, a nominal engine size was determined based on the estimated performance effect of the technologies included in the package and a set of packages with a range of engine sizes larger and smaller than the nominal engine size were simulated. The same performance cycle was run and the sum of the four metrics compared to the baseline sum for each engine size package. Results where the sum was not equal to or less than the baseline sum (more stringent than the 5 percent band suggested by NAS) were rejected. The drive cycle CO_2 emissions of the target package were taken from the lowest emissions result of the remaining results.

For the Proposed Determination, EPA has continued to rely on the performance criteria from the Draft TAR analysis within its analyses of technology effectiveness including ¼ mile time, 0-60 time, 30-50 passing time, and 50-70 passing time performance metrics. Comments were received from AAM, FCA, and Ford, suggesting that top gear gradeability be added as a performance criterion, in particular when applying advanced transmissions. EPA has considered these comments, as noted in Section 2.3.4.2.2. (Effectiveness Values for TRX11 and TRX21), and determined that for advanced transmissions, the performance criteria used in the Draft TAR are sufficient for defining performance neutrality, even if some downshifting occurs under limited high-load conditions.

For the purpose of specification and costing of plug-in vehicles (BEVs and PHEVs, or collectively, PEVs), the Proposed Determination analysis maintains acceleration performance by the same method as in the Draft TAR. EPA derived an empirical equation relating PEV power-to-weight ratio to reported 0-60 acceleration time based on an informal study of MY2012-2017 BEVs and PHEVs. A target 0-60 time was selected for each PEV configuration comparable to that of conventional vehicles, and the motor power assigned based on this equation. The PEV motor sizing methodology is described in more detail in Chapter 2.2.4.4.6 (Relating Power to Acceleration Performance). While performance for these vehicles was only maintained by means of the 0-60 metric, it should be noted that the high low-speed torque of an electric motor is likely to favor the 0-30 metric, thereby making 0-60 the more demanding metric of the two.

2.3.1.3 Fuels

Fuel specifications for the gasoline and diesel fuels used for demonstration of compliance with light-duty vehicle GHG and CAFE standards are contained within the Title 40, Part 86 of the U.S. Code of Federal Regulations. Tabulated values are reproduced here for reference purposes in Table 2.30 and Table 2.31 for gasoline and diesel, respectively. Analyses of the effectiveness of powertrain technologies over the regulatory drive cycles used fuel properties conforming to these specifications.

Table 2.30 Test Fuel Specifications for Gasoline without Ethanol (from 40 CFR §86.113-04)

Item	Regular	Reference Procedure[1]
Research octane, Minimum[2]	93	ASTM D2699; ASTM D2700
Octane sensitivity[2]	7.5	ASTM D2699; ASTM D2700
Distillation Range (°F):		
Evaporated initial boiling point[3]	75-95	ASTM D86
10% evaporated	120-135	
50% evaporated	200-230	
90% evaporated	300-325	
Evaporated final boiling point	415 Maximum	
Hydrocarbon composition (vol %):		
Olefins	10% Maximum	ASTM D1319
Aromatics	35% Maximum	
Saturates	Remainder	
Lead, g/gallon (g/liter), Maximum	0.050 (0.013)	ASTM D3237
Phosphorous, g/gallon (g/liter), Maximum	0.005 (0.0013)	ASTM D3231
Total sulfur, wt. %[4]	0.0015-0.008	ASTM D2622
Dry Vapor Pressure Equivalent (DVPE), psi (kPa)[5]	8.7-9.2 (60.0-63.4)	ASTM D5191

Table 2.31 Petroleum Diesel Test Fuel (from 40 CFR §86.113-94)

Property	Unit	Type 2-D	Reference Procedure[1]
(i) Cetane Number		40-50	ASTM D613
(ii) Cetane Index		40-50	ASTM D976
(iii) Distillation range:			
(A) IBP		340-400 (171.1-204.4)	
(B) 10 pct. Point		400-460 (204.4-237.8)	
(C) 50 pct. Point	°F (°C)	470-540 (243.3-282.2)	STM D86
(D) 90 pct. Point		560-630 (293.3-332.2)	
(E) EP		610-690 (321.1-365.6)	
(iv) Gravity	°API	32-37	ASTM D4052
(v) Total sulfur	ppm	7-15	ASTM D2622
(vi) Hydrocarbon composition: Aromatics, minimum (Remainder shall be paraffins, naphthenes, and olefins)	pct	27	ASTM D5186
(vii) Flashpoint, min	°F (°C)	130 (54.4)	ASTM D93
(viii) Viscosity	centistokes	2.0-3.2	ASTM D445
[1] ASTM procedures are incorporated by reference in §86.1			

EPA's estimate of effectiveness for gasoline-fueled engines and engine technologies was based on Tier 2 Indolene fuel although protection for operation in-use on Tier 3 gasoline (87 AKI E10) was included in the analysis of engine technologies considered both within the Draft TAR and Proposed Determination. Additionally, in the technology assessment for this Proposed Determination, EPA has considered the required engine sizing and associated effectiveness adjustments when performance neutrality is maintained on 87AKI gasoline typical of real-world use. Consistent with its historical practice, when test fuel properties are updated, EPA will determine appropriate test procedure adjustments in order maintain the same level of stringency of the GHG standards when vehicles are tested using Tier 3 certification fuel. A correction factor for application to future vehicles certified to the GHG standards using Tier 3 gasoline that will allow correction of CO_2 emissions in a manner that accounts for differences between Tier 2 and Tier 3 certification fuels is currently under regulatory development with manufacturers, industry, and other stakeholder involvement.

The Alliance of Automobile Manufacturers and several manufacturers commented that the lower octane of Tier 3 fuel degrades efficiency at mid and high load conditions, specifically over the US06 test cycle and similar high load conditions observed in real world conditions. Arguably, any vehicle or engine can experience some degradation of efficiency under certain operating conditions such as high temperature ambient conditions or sustained high loads when climbing a grade or pulling a trailer. Higher octane fuel can reduce degradation in efficiency under these operating conditions and some manufacturers have stated in their owner's manuals a recommendation to use premium fuel under these conditions[520]. Compliance with the GHG standards, however, is demonstrated over the FTP and HWFET cycles, which typically do not involve knock-limited operation and thus do not result in significant changes in knock-limited spark advance and therefore are unlikely to reflect conditions where octane may impact emissions.

Furthermore, preliminary data from EPA chassis dynamometer testing of 10 MY2013 through MY2016 light-duty passenger cars and pickup trucks with a variety of combustion systems (PFI, naturally aspirated GDI, non-HEV GDI Atkinson, turbocharged/downsized GDI) shows a small, incremental reduction in CO_2 emissions of approximately 1 percent over the combined-cycle for Tier 3 gasoline relative to Tier 2 gasoline for all of the vehicles tested. The reduction in CO_2 emissions from Tier 3 gasoline is due in part to the reduced carbon content of Tier 3 gasoline relative to Tier 2 gasoline. This is largely due to a reduction in aromatics for Tier 3 gasoline that is reflective of nationwide trends in U.S. gasoline properties over the past four decades since aromatic content was last revised for gasoline used for EPA certification and compliance testing.

We note further that under current guidelines established in guidance letter "1997-01: New Guidance on Testing Vehicles with Knock Sensors"[521], manufacturers are required at certification to provide confirmation that vehicles that are not labeled as 'premium fuel required' do not see a change in emissions over all test cycles, including the high load US06 cycle, when operated on the regular octane fuel they are likely to see in real world operation. While it is possible that a future engine may be designed to take advantage of higher octane fuels for GHG reductions, EPA did not base the technology choices or effectiveness levels premised on normal operation requiring a high octane fuel. EPA did base technology choices for turbocharged/downsized engines, Miller Cycle engines, and Atkinson Cycle engines on the premise that these engines would continue to use regular-grade 87 AKI fuel as a manufacturer recommended fuel and EPA included the cost of technologies necessary to protect for operation on such fuels, including:

- Sufficient intake camshaft phaser authority to reduce effective compression ratio for pre-ignition knock abatement (ATK2, "advanced" ATK2, and Miller Cycle)
- Use of an integrated exhaust manifold and use of split cylinder head and engine block cooling system control (TDS24, Miller Cycle)
- Use of cooled EGR ("advanced" ATK2, Miller Cycle, TDS24)

Manufacturers always have the option of designating their vehicle as 'premium fuel required' allowing them to perform emission testing using a high octane variant of Tier 3 E10 gasoline.

Fuel effects are also discussed in detail with regard to Atkinson cycle engines in Chapter 2.3.4.1.8 and turbocharged and downsized engines in Chapter 2.3.4.1.9.

2.3.1.4 Vehicle Classification

The determination of the most appropriate values for technology effectiveness and cost depends on the characteristics of the particular vehicle to which the technologies are applied. In the FRM and Draft TAR, the six vehicle classes defined for the purpose of characterizing technology effectiveness were derived from the vehicle size classifications defined in 40 CFR §600.315-08. These classes are based on vehicle interior volume and gross vehicle weight rating attributes, and were defined for the purpose of labeling fuel economy in a way that allows consumers to compare vehicles within commonly recognized market segments. The classification of vehicles for estimation of technology costs in the FRM and Draft TAR accounted for the various engine and valvetrain configurations most prevalent in the baseline fleet, and together with the six effectiveness classes produced a total of 19 vehicle types. While overall this method of grouping placed similar vehicles together, stakeholder comments on the Draft TAR, including those from FCA, highlighted examples where some dissimilar vehicles were assigned the same cost and effectiveness benefits.

For this Proposed Determination assessment, EPA has refined the vehicle classification approach in several ways. First, for the purpose of assigning the most representative estimates for technology effectiveness, EPA has classified vehicles according to the attributes of vehicle road load power and engine power-to-vehicle weight ratio as described in Section 2.3.3.2. Unlike the Draft TAR's size-based effectiveness classifications, the ALPHA model effectiveness estimates are now developed according to low, medium, and high vehicle power-to-weight levels, abbreviated as 'LPW', 'MPW', and 'HPW', respectively. The first two of these are divided further into low and high vehicle road load categories, abbreviated as 'LRL' and 'HRL'. An additional class dedicated to trucks with heavy towing and hauling capability results in a total of six ALPHA classes for technology effectiveness, as shown in Table 2.32.

Table 2.32 ALPHA Classes for Characterizing Technology Effectiveness

ALPHA Class	Power-to-Weight Ratio	Vehicle Road Load
LPW_LRL	Low	Low
LPW_HRL	Low	High
MPW_LRL	Medium	Low
MPW_HRL	Medium	High
HPW	High	-
Truck	-	-

Second, for this Proposed Determination, EPA has refined the classification of vehicle curb weights, which is one of the elements considered when categorizing vehicles for the purpose of assigning technology costs. For the FRM and Draft TAR analyses, the same vehicle grouping that was used for effectiveness classification was also the basis for the vehicle grouping used for cost classification. For example, the unique production-weighted average curb weights for the small car and large car classes were used to calculate technology costs for mass reduction and electrification (battery and non-battery costs) for the vehicles within those classes. For this Proposed Determination, EPA has added a classification by curb weight as shown in Table 2.33, which is independent of the ALPHA classes shown above in Table 2.32. As a result, for this updated analysis, EPA is able to apply technology costs to vehicles within a narrower range of curb weights, thus improving the representativeness of the costs applied. This is particularly relevant for electrification and mass reduction, two technologies for which the costs directly relate to vehicle curb weight.

Table 2.33 Curb Weight Classes for Characterizing Technology Cost

Curb Weight Class	Description	Curb Weight Range (lbs)		Average Curb Weight (lbs) (Volume Weighted)	Std. Dev. (lbs)	Production Volume (MY2015)
		Greater than	Less than or equal			
1	Passenger Vehicle_1	-	3145	2822	220	3,012,100
2	Passenger Vehicle_2	3145	3437	3285	76	2,821,695
3	Passenger Vehicle_3	3437	3729	3554	89	3,083,238
4	Passenger Vehicle_4	3729	4351	3995	164	2,641,538
5	Passenger Vehicle_5	4351	-	4820	486	3,263,377
6	Pickup Truck	-	-	4815	506	1,786,224
7	PEVs (PHEVs/BEVs)	-	-	3772	845	123,836

In EPA's Lumped Parameter Model (LPM) and OMEGA fleet compliance analysis, vehicle types are used to distinguish between vehicles for which fundamental characteristics cause technology cost and effectiveness values to vary. As described above, effectiveness is influenced by road load power and power-to-weight ratio, while cost is influenced by the starting engine configuration, curb weight, and in the case of trucks, a requirement for heavy towing. In addition to the overarching vehicle types, EPA also uses specific data for the baseline vehicles, including the particular technologies applied and power-to-weight ratios in order to produce appropriate estimates of incremental cost and effectiveness for each individual vehicle. EPA's approach for accounting for individual vehicle characteristics when determining appropriate technology effectiveness values is described further in Section 2.3.3.5. The approach for accounting for the previously applied technologies when assigning incremental technology cost and effectiveness values is described further in Chapter 5.3.4.

EPA's third refinement of the vehicle classification approach for this Proposed Determination was to expand the number of vehicle types to 29, an increase from the 19 vehicle types used in the FRM and Draft TAR analyses. The new vehicle type definitions, derived from the combination of cost and effectiveness classifications, are shown in Table 2.34 along with examples of some of the higher volume vehicle models in the MY2015 fleet.

Increasing the number of vehicle types was done in part to accommodate the additional curb weight criteria and revised ALPHA class definitions described above, while also responding to stakeholder comments that the FRM and Draft TAR classification approach tended to group dissimilar vehicles together. In this updated technology assessment, each of the refined 29 vehicle types contain a narrower range of the vehicle characteristics with the greatest influence on technology effectiveness and cost; specifically, power-to-weight ratio, road load power, curb weight, and original engine configuration. Consequently, the higher power-to-weight ratios typical of MY2015 are more appropriately represented in this Proposed Determination than would have been possible with the classification approach used in the FRM and Draft TAR. The overall result of this updated vehicle classification approach is a set of ALPHA classes and vehicle types that provide greater resolution than the 19 vehicle types used in the Draft TAR, and advance the goal of applying the most representative cost and effectiveness estimates for technologies applied to the MY2015 fleet. See Section 2.3.3.2 for more details on the classification approach for effectiveness, and comparison with the Draft TAR and FRM approach.

Table 2.34 Expanded Vehicle Types for Characterizing Technology Cost and Effectiveness

Veh Type	ALPHA Class	Curb Wgt Class	Engine Config	Example	Veh Type	ALPHA Class	Curb Wgt Class	Engine Config	Example
1	LPW_LRL	1	I4 DOHC	Sentra, Corolla	16	MPW_LRL	3	V6 DOHC	IS250
2	MPW_LRL	1	I4 DOHC	Dart, Focus	17	LPW_HRL	3	V6 DOHC	Transit
3	MPW_LRL	2	I4 DOHC	Altima, Camry	18	HPW	4	V6 DOHC	Charger
4	LPW_HRL	2	I4 DOHC	Rogue, Patriot	19	MPW_HRL	4	V6 DOHC	Pathfinder,Journey
5	MPW_LRL	3	I4 DOHC	Malibu, 200	20	HPW	5	V6 DOHC	Camaro
6	LPW_HRL	3	I4 DOHC	Forester, Cherokee	21	MPW_HRL	5	V6 DOHC	Grand Cherokee
7	LPW_HRL	4	I4 DOHC	Outback, Equinox	22	Truck	6	V6 DOHC	Tacoma, Frontier
8	Truck	6	I4 DOHC	Colorado, Tacoma	23	HPW	5	V8 OHV	Charger
9	Truck	6	V6 OHV	Silverado, Sierra	24	MPW_HRL	5	V8 OHV	Tahoe, Suburban
10	HPW	3	V6 SOHC	RDX, TLX	25	Truck	6	V8 OHV	Silverado, Sierra
11	MPW_HRL	4	V6 SOHC	Odyssey	26	HPW	4	V8 DOHC	Mustang, SL550
12	LPW_LRL	1	V6 DOHC	Cruze,Focus turbos	27	HPW	5	V8 DOHC	QX80, GL550
13	MPW_LRL	2	V6 DOHC	Fiesta turbo	28	MPW_HRL	5	V8 DOHC	GX460, Sequoia
14	LPW_LRL	2	V6 DOHC	Passat	29	Truck	6	V8 DOHC	Tundra, F150
15	HPW	3	V6 DOHC	ES350, Impala, Q50					

2.3.2 Approach for Determining Technology Costs

This section reviews the primary sources and approaches EPA uses to estimate technology costs. These costs are divided into several primary types, including direct manufacturing costs, indirect costs, and maintenance and repair costs.

The estimation of direct manufacturing costs includes consideration of cost reduction over time through manufacturer learning. Indirect costs are estimated by application of indirect cost multipliers (ICMs). EPA computes total costs as the sum of direct manufacturing cost (DMC) and indirect cost (IC). This approach was used in the Draft TAR analysis and is also used in this Proposed Determination analysis.

Multiple comments from NGOs (American Council for an Energy-Efficient Economy (ACEEE), Union of Concerned Scientists (UCS), and Environmental Defense Fund (EDF)) supported EPA's use of ICMs rather than retail price equivalents (RPEs) as a means of estimating indirect costs.

We also received some comments on our cost reductions through manufacturer learning. Notably, Ford argued that product cadence does not allow for cost reductions from learning to be realized since new products are constantly being developed. However, the learning effects we estimate should be taken as occurring at the level of the supplier, not that of the automaker. Since we have not estimated efficiency improvements to individual technologies during the time frame of the analysis, we do not believe that such redesign to improve the "current best technology" to the "next best technology" is necessary to achieve the reductions we expect for the costs we have estimated.

2.3.2.1 Direct Manufacturing Costs

Estimates of direct manufacturing costs (DMC) used in this analysis come from many sources, including published technical papers, reports, and analyses, teardown studies contracted by EPA, and supplier- and OEM-provided data (sometimes including confidential business information).

The 2015 NAS Report[522] supported EPA's assessment that teardown studies are perhaps the best source of DMC estimates. NAS encouraged the agencies to make use of tear-down studies where available, stating, “the use of teardown studies has improved the agencies’ estimates of costs” (NAS pp. S-3). This advice was reflected in EPA's continued use of teardown studies to develop many of the technology cost assumptions in the Draft TAR. Public comments on the Draft TAR received from the American Council for an Energy-Efficient Economy (ACEEE) and the Union of Concerned Scientists (UCS) additionally were supportive of EPA's use of teardown studies. The summary below provides more information on our sources for cost information for many of the technologies considered in this analysis.

2.3.2.1.1 Costs from Tear-down Studies

As in the Draft TAR, there are a number of technologies in this analysis that have been costed using the tear-down method. As a general matter, EPA believes, and the NAS agrees,[523] that the most rigorous method to derive technology cost estimates is to conduct studies involving tear-down and analysis of actual vehicle components. A “tear-down” involves breaking down a technology into its fundamental parts and manufacturing processes by completely disassembling actual vehicles and vehicle subsystems and precisely determining what is required for its production. The result of the tear-down is a “bill of materials” for each and every part of the vehicle or vehicle subsystem. This tear-down method of costing technologies is often used by manufacturers to benchmark their products against competitive products. Historically, vehicle and vehicle component tear-down has not been done on a large scale by researchers and regulators due to the expense required for such studies. Many technology cost studies in the literature are based on information collected from OEMs, suppliers, or "experts" in the industry and are thus non-reproducible and non-transparent. In contrast, EPA-sponsored teardown studies are completely transparent and include a tremendous amount of data and analyses to improve accuracy.

While tear-down studies are highly accurate at costing technologies for the year in which the study is intended, their accuracy, like that of all cost projections, may diminish over time as costs are extrapolated further into the future because of uncertainties in predicting commodities (and raw material) prices, labor rates, and manufacturing practices. The projected costs may be higher or lower than predicted.

Since the early development of the 2012-2016 rule, EPA has contracted with FEV, Inc. to conduct tear-down cost studies for a number of key technologies evaluated in assessing the feasibility of future GHG and CAFE standards. The analysis methodology included procedures to scale the tear-down results to smaller and larger vehicles, and also to different technology configurations. FEV's methodology was documented in a report published as part of the MY2012-2016 rulemaking process.[524]

Additional cost studies were completed and used in support of the 2017-2025 FRM. These include vehicle tear downs of a Ford Fusion power-split hybrid and a conventional Ford Fusion (the latter served as a baseline vehicle for comparison). In addition to providing power-split HEV costs, the results for individual components in these vehicles were subsequently used to develop costs for the P2 hybrid used in the following MY2017-2025 FRM.[YY] This approach to costing P2 hybrids was undertaken because P2 HEVs were not yet in volume production at the time of hardware procurement for tear-down. Finally, an automotive lithium-polymer battery was torn down to provide supplemental battery costing information to that associated with the NiMH battery in the Fusion, because automakers were moving to Li-ion battery technologies due to the higher energy and power density of these batteries. As noted, this HEV cost work, including the extension of results to P2 HEVs, has been documented in a report prepared by FEV and was used in support of the 2017-2025 FRM. Because of the complexity and comprehensive scope of this HEV analysis, EPA commissioned a separate peer review focused exclusively on the new tear down costs developed for the HEV analysis. Reviewer comments generally supported FEV's methodology and results, while including a number of suggestions for improvement, many of which were subsequently incorporated into FEV's analysis and EPA final report. The peer review comments and responses were made available in the rulemaking docket.

Some of the technologies for which FEV has completed teardown studies over the course of the contract with EPA are listed below. These completed studies provide a thorough evaluation of these technologies' costs relative to their baseline (or replaced) technologies.

- Stoichiometric gasoline direct injection (SGDI) and turbocharging with engine downsizing (T-DS) on a DOHC (dual overhead cam) I4 engine, replacing a conventional DOHC I4 engine
- SGDI and T-DS on a SOHC (single overhead cam) on a V6 engine, replacing a conventional 3-valve/cylinder SOHC V8 engine
- SGDI and T-DS on a DOHC I4 engine, replacing a DOHC V6 engine
- 6-speed automatic transmission (AT), replacing a 5-speed AT
- 6-speed wet dual clutch transmission (DCT) replacing a 6-speed AT.
- 8-speed AT replacing a 6-speed AT
- 8-speed DCT replacing a 6-speed DCT
- Power-split hybrid (Ford Fusion with I4 engine) compared to a conventional vehicle (Ford Fusion with V6). The results from this tear-down were extended to address P2 hybrids. In addition, costs from individual components in this tear-down study were used by the agencies in developing cost estimates for PHEVs and BEVs.
- Fiat Multi-Air engine technology. (Although results from this cost study are included in the rulemaking docket, they were not used in the 2017-2025 rulemaking's technical

[YY] Examples of production P2 Hybrids are the Hyundai Sonata Hybrid and the Infiniti M35 Hybrid analyses because the technology is under patent and therefore not considered in the 2017-2025 time frame).

In addition, FEV and EPA extrapolated the engine downsizing costs for the following scenarios that were based on the above study cases:

- Downsizing a SOHC 2 valve/cylinder V8 engine to a DOHC V6
- Downsizing a DOHC V8 to a DOHC V6
- Downsizing a SOHC V6 engine to a DOHC 4 cylinder engine
- Downsizing a DOHC 4 cylinder engine to a DOHC 3 cylinder engine

Teardown work was also performed in the area of mass reduction technologies. This work is highlighted in greater detail in Chapter 2.3.4.6 of this TSD.

EPA has relied on the findings of FEV for estimating the cost of the technologies covered by the tear-down studies. However, note that FEV based their costs on the assumption that these technologies would be mature when produced in large volumes (450,000 units or more for each component or subsystem). If manufacturers are not able to employ the technology at the volumes assumed in the FEV analysis with fully learned costs, then the costs for each of these technologies would be expected to be higher. There is also the potential for stranded capital if technologies are introduced too rapidly for some indirect costs to be fully recovered. While EPA considers the FEV tear-down analysis results to be generally valid for the 2022 to 2025 time frame for fully mature, high sales volumes, FEV performed supplemental analysis supporting the FRM to consider potential stranded capital costs, and we have included these in our primary analyses of program costs.

2.3.2.1.2 Electrified Vehicle Battery Costs

As in the 2012 FRM and the Draft TAR, EPA has used the BatPaC model[525] to estimate battery costs for electrified vehicles. Developed by Argonne National Laboratory (ANL) for the Vehicle Technologies Program of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, the BatPaC model allows users to estimate the manufacturing cost of battery packs for various types of electrified powertrains given battery power and energy requirements as well as other design parameters.

In the 2015 NAS report (p. 4-25), the NAS committee endorsed the importance of the use of a bottom-up battery cost model such as BatPaC, further finding that "the battery cost estimates used by the agencies are broadly accurate" (Finding 4.4, p. 4-43). Since the publication of the FRM, BatPaC has been further refined and updated with new costs for some cathode chemistries and cell components, improved thermal management calculations, and improved accounting for plant overhead costs. Further changes were released in late 2015 and include additional chemistries, updated material costs, improved calculation of electrode thickness limits, and improved estimation of cost and energy requirements of certain manufacturing steps and material production processes.[526] EPA has used the most recent version of BatPaC to revise the battery cost projections used in this Proposed Determination analysis, as detailed in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

In the 2012 FRM, the agencies developed cost and effectiveness values for the mild and P2 HEV configurations, two different all-electric mileage ranges for PHEVs (20 and 40 in-use miles) and three different mileage ranges for BEVs (75, 100 and 150 in-use miles). In the Draft TAR analysis, EPA introduced cost and effectiveness values for a new 48-Volt mild hybrid, and changed the 150-mile BEV configuration to a 200-mile configuration. These changes are retained in the current analysis. Additional updates to the cost inputs and methodology applied to electrified vehicles are described in Chapter 2.3.4.3 (Electrification: Data and Assumptions for this Assessment).

2.3.2.1.3 Specific DMC Updates since the Draft TAR

EPA continues to believe that teardown studies are the most robust source of cost estimates. For the Draft TAR, EPA updated costs from other prior teardowns (largely the transmission teardowns) based on updates to those studies performed by FEV and these costs are largely retained for this analysis. EPA also updated battery costs for electrified vehicles based on improvements to battery sizing estimation and an updated set of input metrics to the BatPaC model. EPA has retained the new technologies introduced in the Draft TAR analysis, specifically a 48-Volt mild hybrid, a more capable naturally aspirated Atkinson cycle engine with a high compression ratio, a Miller cycle engine and a 200-mile range electric vehicle. Technology costs for 48V mild hybrid are largely carried over from the estimates in the Draft TAR which were derived from information provided by a previous teardown study of a high-voltage mild hybrid. Costs for the more capable Atkinson cycle engine were based on costs reported by NAS. All technology costs have been updated to 2015 dollars for the Proposed Determination analysis (Draft TAR costs were in 2013 dollars).

2.3.2.1.4 Approach to Cost Reduction through Manufacturer Learning

For some of the technologies considered in this analysis, manufacturer learning effects would be expected to play a role in the actual end costs. The "learning curve" or "experience curve" describes the reduction in unit production costs as a function of accumulated production volume. In theory, the cost behavior it describes applies to cumulative production volume measured at the level of an individual manufacturer, although it is often assumed—as EPA and NHTSA have both done in past regulatory analyses—to apply at the industry-wide level, particularly in industries that utilize many common technologies and component supply sources. EPA believes there are indeed many factors that cause costs to decrease over time. Research in the costs of manufacturing has consistently shown that, as manufacturers gain experience in production, they are able to apply innovations to simplify machining and assembly operations, use lower cost materials, and reduce the number or complexity of component parts. All of these factors allow manufacturers to lower the per-unit cost of production (i.e., the manufacturing learning curve).

NAS recommended that the agencies "continue to conduct and review empirical evidence for the cost reductions that occur in the automobile industry with volume, especially for large-volume technologies that will be relied on to meet the CAFE/GHG standards." (NAS pp. 7-23) EPA has conducted such a review under contract to ICF looking at learning in mobile source industries. The goal of the effort was to provide an updated assessment on learning and its existence in manufacturing industries. An extensive literature review was conducted and the most applicable and appropriate studies were chosen with the help of a subject matter expert

(SME) that is one of the leading experts in this area.[ZZ] EPA hoped that the study would provide clear learning rates that could be applied in various mobile source manufacturing industries rather than the more general learning rates used in the past. That study was completed in September of 2015. In the Draft TAR, we noted that a peer review had been initiated and completed, but the subsequent final report was not completed in time for inclusion in the docket supporting the Draft TAR. That final report, which includes responses to the peer review is now completed and is contained in the docket supporting this Proposed Determination.[527]

In the contracted study, ICF performed this literature review and analysis of learning in the mobile source sector with the assistance of a Subject Matter Expert (Dr. Linda Argote of Carnegie Mellon University). The draft report, Cost Reduction through Learning in Manufacturing Industries and in the Manufacture of Mobile Sources, was subsequently peer-reviewed by three well-known experts in the field of learning (Marvin Lieberman, Ph.D., University of California, Los Angeles (UCLA) Anderson School of Management; Natarajan Balasubramanian, Ph.D., Whitman School of Management, Syracuse University; and Chad Syverson, Ph.D., University of Chicago Booth School of Business). The peer review was carried out for EPA by RTI International based on EPA Science Policy Council Peer Review Handbook, 4th Edition, and was completed in May 2016.

The study consists of two parts: a literature review, and an estimate of a mobile source progress ratio. A total of 53 studies on learning were examined, with 20 of these selected for detailed review (the other 33 received a more cursory review and are not discussed in detail in the report). Five of these studies were used as the basis to estimate the progress ratio for the mobile source sector. On the basis of these studies, the SME noted: "The mean learning rate is estimated to be -0.245, with a standard error of 0.0039. Thus, the lower bound for a 95 percent confidence interval for the learning rate is -0.253; the upper bound is -0.238. These estimates translate into a mean progress ratio of 84.3 percent. The confidence interval around this number ranges from 83.9 percent to 84.8 percent, suggesting that one can be reasonably confident that the progress ratio falls in this interval. Thus, the best estimate of the progress ratio in mobile source industries is 84 percent." This is the value that EPA used in both the Draft TAR and this Proposed Determination.

As a result, the learning curve recommended for use by the report has slightly lower learning rates than those EPA has used in the past. Past EPA studies have used a learning rate based on a curve that resulted in a 20 percent cost reduction for each doubling of volume; the recommended rate results in cost reductions of 15 percent. As such, EPA has updated learning rates to be consistent with the recommendation of the report. The curve used in this analysis is:

$$y_{t+1} = ax_{t+1}^{b}$$

Where:

y_{t+1} = Costs required to produce a unit at time t+1

a = Costs required to produce the first unit

x_{t+1} = Cumulative number of units produced through period t+1

[ZZ] The SME was Dr. Linda Argote of Carnegie Mellon University.

b = A parameter measuring the rate at which unit costs change as cumulative output increases; i.e., the learning rate

For this analysis, EPA has used this equation to estimate the learning effects and have generated the learning curves shown below. How these learning curves were actually generated using the above curve is described in a memorandum contained in the docket.[528] In general, the new learning factors were generated in a way to provide similar results to past analyses. However, because the new rate is lower, there are subtle differences especially in years further from the "base" year (i.e., the year where the learning factor is 1.0). The docket memorandum makes this clearer by providing the new factors alongside the factors used in the 2012 FRM for comparison. Note that the factors used in this Proposed Determination are identical to those used in the Draft TAR.

Learning effects are applied to most but not all technologies because some of the expected technologies are already used rather widely in the industry and, presumably, learning impacts have already occurred. Learning effects on the steep-portion of the learning curve was applied for only a handful of technologies that are considered to be new or emerging technologies. Most technologies have been considered to be more established given their current use in the fleet and, hence, learning effects on the flat portion of the learning curve have been applied. The learning factor curve applied to each technology are summarized in Table 2.35 with the actual year-by-year factors for each corresponding curve shown in Table 2.36.

Table 2.35 Learning Effect Algorithms Applied to Technologies Used in this Analysis

Technology	Learning Factor "Curve"[a]
Aero, active	24
Aero, passive	24
Atkinson, level 1	24
Atkinson, level 2	24
Cam configuration changes	
V6 OHV to V6 DOHC	28
V6 SOHC to V6 DOHC	23
V8 OHV to V8 DOHC	28
V8 SOHC to V8 DOHC	23
V8 SOHC3V to V8 DOHC	23
Charger, in-home, BEV	26
Charger, in-home, PHEV20	26
Charger, in-home, PHEV40	26
Charger, in-home, labor	1
Cylinder deactivation	24
Direct injection, stoichiometric, gasoline	23
Diesel, advanced (Tier3)	23
Diesel, lean NOx trap	23
Diesel, selective catalytic reduction	23
Downsizing, associated with turbocharging	
I4 DOHC to I3 DOHC	23
I4 DOHC to I4 DOHC	23
V6 OHV to I4 DOHC	28
V6 SOHC to I4 DOHC	23
V6 DOHC to I4 DOHC	23
V8 OHV to V6 DOHC	28
V8 SOHC to V6 DOHC	23
V8 SOHC3V to V6 DOHC	23
Engine friction reduction, level 1	1
Engine friction reduction, level 2	1
EGR, cooled	23
Electric power steering	24
BEV75, battery pack	26
BEV100, battery pack	26
BEV200, battery pack	26
BEV75, non-battery items	28
BEV100, non-battery items	28
BEV200, non-battery items	28
HEV, Mild, battery pack	31
HEV, Mild, non-battery items	23
HEV, Strong, battery pack	31
HEV, Strong, non-battery items	23
HEV, Plug-in, battery pack	26
HEV, Plug-in, non-battery items	23
Improved accessories, level 1	24
Improved accessories, level 2	24
Low drag brakes	1
Lower rolling resistance tires, level 1	1

Lower rolling resistance tires, level 2	32
Lube, engine changes to accommodate low friction lubes	1
Mass reduction <15%	30
Mass reduction >=15%	30
Secondary axle disconnect	24
Stop-start	25
Turbo, 18-21 bar	23
Turbo, 24 bar	23
Turbo, Miller-cycle	23
TRX11/12	23
TRX21/22	23

Note:
[a] See table below.

The actual year-by-year factors for the numbered curves shown in Table 2.36.

Table 2.36 Year-by-year Learning Curve Factors for the Learning Curves Used in this Analysis

Curve	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
22	1.37	1.33	1.29	1.25	1.21	1.18	1.15	1.13	1.11	1.08	1.06	1.04	1.02	1.00
23	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85	0.84	0.83	0.82	0.82
24	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85	0.84
25	2.03	1.62	1.28	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67	0.66	0.64
26	3.05	2.44	2.11	1.89	1.74	1.61	1.51	1.43	1.36	1.30	1.25	1.20	1.16	1.12
27	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67	0.66	0.64	0.63	0.62	0.61
28	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87	0.85
29	1.17	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91	0.89	0.88	0.87
30	1.29	1.24	1.20	1.17	1.13	1.09	1.06	1.03	1.00	0.98	0.96	0.94	0.92	0.91
31	3.18	2.54	2.03	1.62	1.28	1.00	0.91	0.84	0.80	0.76	0.74	0.71	0.69	0.67
32	1.74	1.61	1.51	1.43	1.36	1.30	1.25	1.20	1.16	1.12	1.09	1.06	1.04	1.01

Importantly, where the factors shown in Table 2.36 equal “1.00” represents the year for which any particular technology’s cost is based. Thus, if curve 1 is applied to a technology – such as in the case of low friction lubes - it assumes no additional learning takes place over time. In the case of stop-start technology, curve 25 is applied. In this case, the cost estimate used for stop-start is considered a MY2015 cost. Therefore, its learning factor equals 1.00 in 2015 and then decreases going forward to represent lower costs due to learning effects. Its learning factors are greater than 1.00 in years before 2015 to represent “reverse” learning, i.e., higher costs than our 2015 estimate since production volumes have, presumably, not yet reached the point where our cost estimate can be considered valid. Not all of the learning curve factors follow this rule using the updated curve approach used in the Draft TAR and in this Proposed Determination. Also of interest is that only curves 25 (stop-start), 26 (BEV & PHEV batteries) and 31 (mild and strong HEV batteries) show any steeper learning beyond the 2017 to 2020 time frame, and even those curves show less than 5 percent year-over-year cost reductions beyond 2020. In other words, most curves are well into the flatter portion of the learning curve, and even those that are not are well beyond the steep learning that occurs at the early stages of learning, by the time frame considered in this analysis.

Because of the nature of full electric and plug-in electric vehicle battery pack development, the industry is arguably early in the learning-by-doing phase for the types of batteries considered. Our approach, consistent with that used in the FRM, has been to develop a direct manufacturing cost based on sales of 450,000 units. EPA has considered that to be a valid MY2025 cost (i.e., the cost is based in 2025). With that as the MY2025 cost, the costs are considered as understood today and a best fit learning curve is projected between the costs in those near-term and long-term years. This is described in more detail in the docket memorandum mentioned earlier.[529] Note that the 450,000 unit sales is considered a valid MY2025 volume for batteries because that volume is meant to represent volumes at a given production line (a battery supplier production line, not an OEM vehicle production line) and takes into consideration worldwide demand for automotive and other mobile source battery packs, not just U.S.-directed automotive battery packs.

Note that the effects of learning on individual technology costs can be seen in the cost tables presented in Section 2.3.4, below. For each technology, the direct manufacturing costs for the years 2017 through 2025 are shown. The changes shown in the direct manufacturing costs from year-to-year reflect the cost changes due to learning effects.

2.3.2.2 Indirect Costs

2.3.2.2.1 Methodologies for Determining Indirect Costs

To produce a unit of output, vehicle manufacturers incur direct and indirect costs. Direct costs include cost of materials and labor costs. Indirect costs are all the costs associated with producing the unit of output that are not direct costs – for example, they may be related to production (such as research and development [R&D]), corporate operations (such as salaries, pensions, and health care costs for corporate staff), or selling (such as transportation, dealer support, and marketing). Indirect costs are generally recovered by allocating a share of the costs to each unit of good sold. Although it is possible to account for direct costs allocated to each unit of good sold, it is more challenging to account for indirect costs allocated to a unit of goods sold. To make a cost analysis process more feasible, markup factors, which relate total indirect costs to total direct costs, have been developed. These factors are often referred to as retail price equivalent (RPE) multipliers.

Cost analysts and regulatory agencies (including both EPA and NHTSA) have frequently used these multipliers to predict the resultant impact on costs associated with manufacturers' responses to regulatory requirements. The best approach, if it were possible, to determining the impact of changes in direct manufacturing costs on a manufacturer's indirect costs would be to actually estimate the cost impact on each indirect cost element. However, doing this within the constraints of an agency's time or budget is not always feasible, or the technical, financial, and accounting information to carry out such an analysis may simply be unavailable.

RPE multipliers provide, at an aggregate level, the relative shares of revenues (Revenue = Direct Costs + Indirect Costs + Net Income) to direct manufacturing costs. Using RPE multipliers implicitly assumes that incremental changes in direct manufacturing costs produce common incremental changes in all indirect cost contributors as well as net income. However, a concern in using the RPE multiplier in cost analysis for new technologies added in response to regulatory requirements is that the indirect costs of vehicle modifications are not likely to be the same for different technologies. For example, less complex technologies could require fewer

R&D efforts or less warranty coverage than more complex technologies. In addition, some simple technological adjustments may, for example, have no effect on the number of corporate personnel and the indirect costs attributable to those personnel. The use of RPEs, with their assumption that all technologies have the same proportion of indirect costs, is likely to overestimate the costs of less complex technologies and underestimate the costs of more complex technologies.

To address this concern, modified multipliers have been developed by EPA, working with a contractor, for use in rulemakings.[530] These multipliers are referred to as indirect cost multipliers (or ICMs). In contrast to RPE multipliers, ICMs assign unique incremental changes to each indirect cost contributor as well as net income.

ICM = (direct cost + adjusted indirect cost)/(direct cost)

Developing the ICMs from the RPE multipliers requires developing adjustment factors based on the complexity of the technology and the time frame under consideration: the less complex a technology, the lower its ICM, and the longer the time frame for applying the technology, the lower the ICM. This methodology was used in the cost estimation for the recent light-duty MYs 2012-2016 and MYs 2017-2025 rulemaking and for the heavy-duty MYs 2014-2018 rulemaking. There was no serious disagreement with this approach in the public comments to any of these rulemakings. The ICMs for the light-duty context were developed in a peer-reviewed report from RTI International and were subsequently discussed in a peer-reviewed journal article.[531] Importantly, since publication of that peer-reviewed journal article, the EPA has revised the methodology to include a return on capital (i.e., profits) based on the assumption implicit in ICMs (and RPEs) that capital costs are proportional to direct costs, and businesses need to be able to earn returns on their investments.

There is some level of uncertainty surrounding both the ICM and RPE markup factors. The ICM estimates used in the Draft TAR and this Proposed Determination, consistent with the FRM, group all technologies into three broad categories and treat them as if individual technologies within each of the three categories (low, medium, and high complexity) will have exactly the same ratio of indirect costs to direct costs. This simplification means it is likely that the direct cost for some technologies within a category will be higher and some lower than the estimate for the category in general. Additionally, the ICM estimates were developed using adjustment factors developed in two separate occasions: the first, a consensus process, was reported in the RTI report; the second, a modified Delphi method, was conducted separately and reported in an EPA memorandum. Both these panels were composed of EPA staff members with previous background in the automobile industry; the memberships of the two panels overlapped but were not the same. The panels evaluated each element of the industry's RPE estimates and estimated the degree to which those elements would be expected to change in proportion to changes in direct manufacturing costs. The method and the estimates in the RTI report were peer reviewed by three industry experts and subsequently by reviewers for the International Journal of Production Economics. However, the ICM estimates have not yet been validated through a direct accounting of actual indirect costs for individual technologies. RPEs themselves are also inherently difficult to estimate because the accounting statements of manufacturers do not neatly categorize all cost elements as either direct or indirect costs. Hence, each researcher developing an RPE estimate must apply a certain amount of judgment to the allocation of the costs. Since empirical estimates of ICMs are ultimately derived from the same data used to measure RPEs, this affects both measures. However, the value of RPE has not been measured for specific technologies, or for groups of specific technologies. Thus applying a single average RPE to any given technology by definition overstates costs for very simple technologies, or understates them for advanced technologies.

2.3.2.2.2 Indirect Cost Estimates Used in this Analysis

Since their original development in February 2009, the agencies made changes to both the ICM factors and to the method of applying those factors relative to the factors developed by RTI and presented in their reports. These changes have been described and explained in several rulemakings over the years, most notably the 2017-2025 FRM and the more recent Heavy-duty GHG Phase 2 final rule (81 FR 73478).

Although the Draft TAR analysis assessed indirect costs using both the ICM and RPE approaches, EPA has focused on the ICM approach for the Proposed Determination analysis, considering ICMs to be the better means of estimating indirect cost impacts resulting from regulatory changes. EPA believes that this stance is consistent with the support expressed by NAS in their 2015 report,[AAA] as well as several commenters on the Draft TAR. Comments from the American Council for an Energy-Efficient Economy (ACEEE), the Union of Concerned Scientists (UCS), and Environmental Defense Fund (EDF) all supported the use of ICMs. EPA has also performed a sensitivity analysis using RPEs instead of ICMs, as discussed in Section C.1.2 of the Proposed Determination Appendix.

For this Proposed Determination, EPA is assessing indirect costs using the same ICMs as used in the Draft TAR, as shown in Table 2.37. Near term values account for differences in the levels of R&D, tooling, and other indirect costs that will be incurred. Once the program has been fully implemented, some of the indirect costs will no longer be attributable to the standards and, as such, a lower ICM factor is applied to direct costs.

Table 2.37 Indirect Cost Multipliers Used in this Analysis[532]

	2017-2025 FRM and TSD	
Complexity	Near term	Long term
Low	1.24	1.19
Medium	1.39	1.29
High1	1.56	1.35
High2	1.77	1.50

There are two important aspects to the ICM method employed by EPA. First, the ICM consists of two portions: a small warranty-related term and a second, larger term to cover all other indirect costs elements. The breakout of warranty versus non-warranty portions to the ICMs are presented in Table 2.38. The latter of these terms does not decrease with learning and, instead, remains constant year-over-year despite learning effects which serve to decrease direct manufacturing costs. Learning effects were described above. The second important note is that

[AAA] In the 2015 NAS study, the committee stated: "The committee conceptually agrees with the Agencies' method of using an indirect cost multiplier instead of a retail price equivalent to estimate the costs of each technology since ICM takes into account design challenges and the activities required to implement each technology." (NAS Finding 7.1) all indirect costs are forced to be positive, even for those technologies estimated to have negative direct manufacturing costs.

Table 2.38 Warranty and Non-Warranty Portions of ICMs

	Near term		Long term	
Complexity	Warranty	Non-warranty	Warranty	Non-warranty
Low	0.012	0.230	0.005	0.187
Medium	0.045	0.343	0.031	0.259
High1	0.065	0.499	0.032	0.314
High2	0.074	0.696	0.049	0.448

The complexity levels and subsequent ICMs applied throughout this analysis for each technology are shown in Table 2.39 and are identical to those used in the Draft TAR.

Table 2.39 Indirect Cost Markups (ICMs) and Near Term/Long Term Cutoffs Used in EPA's Analysis

Technology	ICM Complexity	Short term thru
Aero, active	Low2	2018
Aero, passive	Med2	2024
Atkinson, level 1	Med2	2018
Atkinson, level 2	Med2	2024
Cam configuration changes		
V6 OHV to V6 DOHC	Med2	2018
V6 SOHC to V6 DOHC	Med2	2018
V8 OHV to V8 DOHC	Med2	2018
V8 SOHC to V8 DOHC	Med2	2018
V8 SOHC3V to V8 DOHC	Med2	2018
Charger, in-home, BEV	High1	2024
Charger, in-home, PHEV20	High1	2024
Charger, in-home, PHEV40	High1	2024
Charger, in-home, labor	None	2024
Cylinder deactivation	Med2	2018
Direct injection, stoichiometric, gasoline	Med2	2018
Diesel, advanced (Tier3)	Med2	2018
Diesel, lean NOx trap	Med2	2018
Diesel, selective catalytic reduction	Med2	2018
Downsizing, associated with turbocharging		
I4 DOHC to I3 DOHC	Med2	2018
I4 DOHC to I4 DOHC	Med2	2018
V6 OHV to I4 DOHC	Med2	2018
V6 SOHC to I4 DOHC	Med2	2018
V6 DOHC to I4 DOHC	Med2	2018
V8 OHV to V6 DOHC	Med2	2018
V8 SOHC to V6 DOHC	Med2	2018
V8 SOHC3V to V6 DOHC	Med2	2018
Engine friction reduction, level 1	Low2	2018
Engine friction reduction, level 2	Low2	2024
EGR, cooled	Med2	2024
Electric power steering	Low2	2018
BEV75, battery pack	High2	2024

BEV100, battery pack	High2	2024
BEV200, battery pack	High2	2024
BEV75, non-battery items	High2	2024
BEV100, non-battery items	High2	2024
BEV200, non-battery items	High2	2024
HEV, Mild, battery pack	High1	2024
HEV, Mild, non-battery items	Med2	2018
HEV, Strong, battery pack	High1	2024
HEV, Strong, non-battery items	High1	2018
HEV, Plug-in, battery pack	High2	2024
HEV, Plug-in, non-battery items	High1	2018
Improved accessories, level 1	Low2	2018
Improved accessories, level 2	Low2	2018
Low drag brakes	Low2	2018
Lower rolling resistance tires, level 1	Low2	2018
Lower rolling resistance tires, level 2	Low2	2018
Lube, engine changes to accommodate low friction lubes	Low2	2018
Mass reduction <15%	Low2	2024
Mass reduction >=15%	Med2	2024
Secondary axle disconnect	Low2	2018
Stop-start	Med2	2018
Turbo, 18-21 bar	Med2	2018
Turbo, 24 bar	Med2	2024
Turbo, Miller-cycle	Med2	2024
TRX11/12	Low2	2018
TRX21/22	Low2	2024

For mass reduction costs in the Draft TAR, EPA developed a new approach to calculating indirect costs due to the unique nature of the direct manufacturing costs that EPA has developed (see Draft TAR Section 5.3.4.6.1). We are using the same approach in this Proposed Determination. Mass reduction strategies, unlike other efficiency technologies, often involve multiple systems and components on a vehicle. A portion of the indirect costs for parts that have design and production outsourced to suppliers are incorporated into the direct manufacturing cost estimates. Components that are designed in-house and possibly produced in-house by the manufacturer, such as the body and frame structures, have higher indirect costs applied. This distinction between supplier and in-house parts is consistent with the recommendations of a study done by Argonne National Laboratory.[533] In that study, the authors suggested retail price equivalent markups of 1.5x direct costs for parts sourced from a supplier, and 2x direct costs for parts sourced internally. The end result, presumably, is an equal total cost, but the markups account for differences in where the indirect costs are incurred. Using that as a basis EPA adjusted the supplied technology ICMs (shown in Table 2.37) by the ratio 2/1.5 to determine in-house ICMs at the "engineered solution" mass reduction point (see Draft TAR Sections 5.3.4.6.1.1 and 5.3.4.6.1.2) which happened to be approximately 20 percent mass reduction level for the car teardown study and the truck teardown study. Since those mass reduction levels were deemed "medium" complexity levels in the FRM, and because EPA still believes that to be a good assessment of the complexity level, EPA has worked with only the medium complexity ICMs in the context of mass reduction. As a result, the ICMs used for mass reduction are as shown in Table 2.40.

Table 2.40 Mass Reduction Markup Factors used by EPA in this TSD

	Supplier Provided Mass Reduction		In-house Provided Mass Reduction	
Markup & Complexity	Near term	Long term	Near term	Long term
ICM - Medium complexity	1.39	1.29	1.85	1.72

The final element of the unique nature of the indirect cost calculations developed by EPA for mass reduction in this analysis, is to calculate the indirect costs using the above ICMs only at the engineered solution point. Notably, EPA applied the markups to the sum of the absolute values of all mass reduction ideas throughout the entire direct manufacturing cost curve. In that way, negative direct costs that are projected at the lower mass reduction levels still have a positive impact on calculated indirect costs. Once the indirect costs were determined via this methodology at the engineered solution, EPA generated an indirect cost curve extending through $0/kg at 0 percent mass reduction and $8.75/kg/% at the engineered solution for cars and $13.23/kg/% for trucks (see Table 2.41 and Table 2.42 for the values of X). The indirect costs at all mass reduction levels between those points lie on that generated cost curve. Inherent in this approach is the assumption that the proportion of mass reduction from supplier and in-house components remains constant at all levels of mass reduction, based on the proportion at the engineered solution. Those curves are shown in Table 2.41 for cars and in Table 2.42 for trucks.

Table 2.41 Mass Reduction Indirect Cost Curves used by EPA for Cars Using ICMs (dollar values in 2013$)

		$/kg DMC*	ICM	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near term	Supplied tech DMC	$1.75	0.39	$0.678	$0.678+0.986=1.66	$8.75x
	In-house tech DMC	$1.16	0.85	$0.986		
Long term	Supplied tech DMC	$1.75	0.29	$0.507	$0.507+0.835=1.34	$7.06x
	In-house tech DMC	$1.16	0.72	$0.835		

Notes:
* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

Table 2.42 Mass Reduction Indirect Cost Curves used by EPA for Trucks Using ICMs (dollar values in 2013$)

		$/kg DMC*	ICM	$/kg IC at Engineered Solution	$/kg IC at Engineered Solution	$/kg/% IC curve**
Near term	Supplied tech DMC	$2.59	0.39	$1.00	$1.00+1.78=2.78	$13.23x
	In-house tech DMC	$2.09	0.85	$1.78		
Long term	Supplied tech DMC	$2.59	0.29	$0.75	$0.75+1.50=2.25	$10.73x
	In-house tech DMC	$2.09	0.72	$1.50		

Notes:

* Calculated as the absolute value of all direct manufacturing costs needed to achieve the engineered solution.
** Where x is the percent mass reduction.

2.3.2.3 Maintenance and Repair Costs

2.3.2.3.1 Maintenance Costs

To estimate maintenance costs that could reasonably be attributed to the 2017-2025 standards, EPA and NHTSA looked—in the 2017-2025 FRM—at vehicle models for which there exists a version with a fuel efficiency and GHG emissions improving technology and a version with the corresponding baseline technology. The difference between maintenance costs for the two models represent a cost which the agencies attributed to the standards. For example, the Ford Escape Hybrid versus the Ford Escape V6 was considered when estimating the types of maintenance cost differences that might be present for a hybrid vehicle versus a non-hybrid, and a Ford F150 with EcoBoost versus the Ford F150 5.0L was considered when estimating the types of maintenance cost differences that might be present for a turbocharged and downsized versus a naturally aspirated engine. In the case of low rolling resistance tires, specific parts were considered rather than specific vehicle models.

By comparing the manufacturer recommended maintenance schedule of the items compared, the differences in maintenance intervals for the two was estimated. With estimates of the costs per maintenance event, a picture of the maintenance cost differences associated with the "new" technology was developed.

EPA continues to believe that the maintenance estimates used in the FRM are reasonable and have therefore used them again in this analysis as we did in the Draft TAR. EPA distinguished maintenance from repair costs as follows: maintenance costs are those costs that are required to keep a vehicle properly maintained and, as such, are usually recommended by auto makers to be conducted on a regular, periodic schedule. Examples of maintenance costs are oil and air filter changes, tire replacements, etc. Repair costs are those costs that are unexpected and, as such, occur randomly and uniquely for every driver, if at all. Examples of repair costs would be parts replacement following an accident or a mechanical failure, etc.

In Chapter 3.6 of the final joint TSD supporting the 2012 FRM, the agencies presented a lengthy discussion of maintenance costs and the impacts projected as part of that rule.[534] Table 2.43 shows the results of that analysis, the maintenance impacts used in the 2012 FRM and again in this analysis, although the costs here have been updated to 2015$. Note that the technologies shown in Table 2.43 are those for which EPA believes that maintenance costs would change; it is clearly not a complete list of technologies expected to meet the MY2025 standards.

Table 2.43 Maintenance Event Costs & Intervals (2015$)

New Technology	Reference Technology	Cost per Maintenance Event	Maintenance Interval (miles)
Low rolling resistance tires level 1	Standard tires	$6.91	40,000
Low rolling resistance tires level 2	Standard tires	$53.03	40,000
Diesel fuel filter replacement	Gasoline vehicle	$53.52	20,000
BEV oil change	Gasoline vehicle	-$42.02	7,500
BEV air filter replacement	Gasoline vehicle	-$31.08	30,000
BEV engine coolant replacement	Gasoline vehicle	-$64.12	100,000

BEV spark plug replacement	Gasoline vehicle	-$90.20	105,000
BEV/PHEV battery coolant replacement	Gasoline vehicle	$127.15	150,000
BEV/PHEV battery health check	Gasoline vehicle	$42.02	15,000

Note that many of the maintenance event costs for BEVs are negative. The negative values represent savings since BEVs do not incur these costs while their gasoline counterparts do. Note also that the 2010 FRM is expected to result in widespread use of low rolling resistance tires level 1 (LRRT1) on the order of 85 percent penetration. Therefore, as 2012 FRM results in increasing use of low rolling resistance tire level 2 (LRRT2), there is a corresponding decrease in the use of LRRT1. As such, as LRRT2 maintenance costs increase with increasing market penetration, LRRT1 maintenance costs decrease. Importantly, the maintenance costs associated with lower rolling resistance tires is the incremental cost of the tires at replacement; it is not associated in any way with a decrease in durability of these tires.

2.3.2.3.2 *Repair Costs*

EPA's analysis accounts for the costs of repairs covered by manufacturers' warranties, and a sensitivity analysis estimated costs for post-warranty repairs**.** The indirect cost multipliers (ICMs) applied in the EPA's analyses include a component representing manufacturers' warranty costs. For the cost of repairs not covered by OEMs' warranties, EPA has, in the past, evaluated the potential to apply an approach similar to that described above for maintenance costs. As for specific scheduled maintenance items, the ALLDATA subscription database applied above provides estimates of labor and part costs for specific repairs to specific vehicle models. However, although ALLDATA also provides service intervals for scheduled maintenance items, it does not provide estimates of the frequency at which specific failures may be expected to occur over a vehicle's useful life. EPA has not yet been able to develop an alternative method to estimate the frequencies of different types of repairs, and are therefore unable to apply these ALLDATA estimates in order to quantify the cost of repairs throughout vehicles' useful lives. Moreover, the frequency of repair of technologies that do not yet exist in the fleet, or are only emerging today provides insufficient representation of what they will be in the future with wider penetration of those technologies. As a result, while the ICMs include costs to cover warranty repairs, we do not consider any additional repair costs as a result of our GHG standards. This is consistent with EPA's approach in both the 2010 and 2012 FRMs and the Draft TAR.

2.3.2.4 Costs Updated to 2015 Dollars

EPA is using technology costs from many different sources. These sources, having been published in different years, present costs in different year dollars (e.g., 2009 dollars or 2012 dollars). For this analysis, EPA sought to have all costs in terms of 2015 dollars to be consistent with the dollars used by EIA in its Annual Energy Outlook 2016. These values are updated from the Draft TAR which expressed costs in 2013 dollars. While the factors used to convert from 20013 dollars (or other) to 2015 dollars are small, EPA prefers to be overly diligent in this regard to ensure consistency across our analyses. EPA has used the GDP Implicit Price Deflator for Gross Domestic Product as the converter, with the actual factors used as shown in Table 2.44.

Table 2.44 Implicit Price Deflators and Conversion Factors for Conversion to 2015$

Calendar Year →	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Implicit Price Deflators for Gross Domestic Product	94.814	97.337	99.246	100	101.221	103.311	105.214	106.913	108.828	109.998
Factor applied to convert to 2013$	1.160	1.130	1.108	1.100	1.087	1.065	1.045	1.029	1.011	1.000

Source: Bureau of Economic Analysis, Table 1.1.9 Implicit Price Deflators for Gross Domestic Product; last revised on September 29, 2016; accessed on 10/29/2016 at www.bea.gov.

2.3.3 Approach for Determining Technology Effectiveness

In the Draft TAR, EPA reevaluated the effectiveness values for all technologies discussed in the MYs2017-2025 light duty GHG Final Rulemaking (FRM), as well as prominent technologies that have emerged since then. Along with the vehicle benchmarking and full vehicle simulation process, EPA reviewed available data including the 2015 LD National Academy of Sciences report[535], confidential manufacturer estimates, automaker and supplier meetings, technical conferences, literature reviews, and press announcements regarding technology effectiveness. For this Proposed Determination EPA has again reevaluated the effectiveness values used in the Draft TAR based on new data and information obtained since then, and assessed the public comments received on the Draft TAR. In most cases, multiple sources of information were considered in the process of determining the effectiveness values used in this Proposed Determination.

Full vehicle simulation modeling has been used in previous light-duty greenhouse gas rules and in the Draft TAR to establish the effectiveness of technologies, and is regularly applied by vehicle manufacturers, suppliers, and academia to evaluate and choose alternative technologies to improve vehicle efficiency. In the 2015 NAS report,[535] the committee recognized the important contribution of full vehicle simulation and lumped parameter modeling in these previous rulemakings, and recommended continued use of these methods as the best way of assessing technologies and the combination of technologies.

For this Proposed Determination as in the Draft TAR, EPA is employing its own full vehicle simulation model: the Advanced Light-duty Powertrain and Hybrid Analysis tool (ALPHA). The ALPHA model has been developed and refined over several years and used in multiple rulemakings to evaluate the effectiveness of vehicle technology packages. The same base model used in the LD ALPHA model was also used in the GEM model for the HD Phase 1 and HD Phase 2 rulemakings. See 81 FR 73530-549 (Oct. 25, 2016. Using ALPHA improves the transparency of the process and provides additional flexibility to allow consideration of the most recent technological developments and vehicle implementations of technologies. Input data for the ALPHA model has been created largely through benchmarking activities. Benchmarking is a commonly used technique that is intended to create a detailed characterization of a vehicle's operation and performance. For the purposes of developing ALPHA, and for establishing overall technology effectiveness, EPA performed many benchmarking activities including measuring vehicle performance over the standard emission cycles and measuring system and component performance on various test stands.

2.3.3.1 Vehicle Benchmarking

As part of its mandated evaluation of the appropriateness of the MY2022-2025 standards, EPA is re-assessing any potential changes to the cost and the effectiveness of advanced technologies available to manufacturers. See section 86.1818-12 (h)(i), (ii), and (iii). Benchmarking is a process by which detailed vehicle, system, and component performance is characterized. Benchmarking is commonly used by vehicle manufacturers, automotive suppliers, national laboratories, and universities in order to gain a better understanding of how vehicles are engineered and to create large datasets that can be applied in modeling and other analyses. In its effort to assess light-duty vehicles in preparation for the MTE, EPA has benchmarked over twenty commercially available vehicles that represent a diverse cross section of the current light-duty fleet, with the results summarized in 15 peer-reviewed SAE papers.[536] [537] As the result of these activities, EPA has calibrated the ALPHA full vehicle simulation model and applied the results of this model to establish and confirm technology effectiveness. In addition, EPA has been able to capture the performance of current vehicles, which is an important goal of the MTE. The performance measurements not only include greenhouse gas emissions and fuel economy, but also account for the additional fuel consumption associated for noise, vibration and harshness (NVH), drivability and criteria emissions controls.

The ALPHA model has been used to confirm and update, where necessary, efficiency data from the previous studies, such as from advanced downsized turbo and naturally aspirated engines. It is also being used to quantify effectiveness from advanced technologies that the agencies did not project to be part of a compliance pathway during the FRM, such as continuously variable transmissions (CVTs), multi-mode normally aspirated engines, and clean diesel engines. The ALPHA model accounts for synergistic effects between technologies and has been used by EPA to calibrate the Lumped Parameter Model to incorporate the latest technology package effectiveness data into the OMEGA compliance model. This process allows EPA to simulate technology combinations (packages) that may not yet exist in the fleet.

To simulate drive cycle performance, the ALPHA model requires various vehicle input parameters, including vehicle inertia and road loads, and component efficiencies and operations. Vehicle benchmarking is the detailed process for obtaining these parameters.

2.3.3.1.1 Detailed Vehicle Benchmarking Process

The following discussion describes the vehicle benchmarking elements used as required for the vehicles tested by EPA leading up to the Proposed Determination. The vehicle benchmarked in this example is a 2013 Chevy Malibu 1LS as detailed in Table 2.45. This vehicle was chosen as representative of a midsize car with a typical conventional powertrain with a naturally aspirated engine and a 6-speed automatic transmission. The first task of the vehicle benchmarking process involved collecting data from on-road and dynamometer testing (Figure 2.69) before removing the engine and transmission for separate component testing. Major components such as the engine and transmission of a vehicle must be isolated and evaluated separately to create accurate performance maps to be included in the ALPHA model.

Table 2.45 Benchmark Vehicle Description

Model	2013 Chevy Malibu 1LS
Engine	2.5L inline-4, GDI, naturally aspirated
Powertrain	Conventional FWD 6-speed automatic, GM6T40 transmission
Gear Ratios	4.584, 2.965, 1.912, 1.446, 1.000, 0.746 with 2.89 final drive
Tire Size	215/60/R16

EPA Label Fuel Economy	22 City, 34 Highway, 26 Combined MPG
Emissions Equivalent Test Weight (ETW)	4,000 lbs (1814 kg)
Emissions Target Road Load A	38.08 lbs (169.4 N)
Emissions Target Road Load B	0.2259 lbs/mph (2.248 N/m/s)
Emissions Target Road Load C	0.01944 lbs/mph^2 (0.4327 N/(m/s)^2)
Fuel Economy ETW	3,625 lbs (1644 kg)
Fuel Economy Target Road Load A	28.62 lbs (127.3 N)
Fuel Economy Target Road Load B	0.1872 lbs/mph (1.863 N/m/s)
Fuel Economy Target Road Load C	0.01828 lbs/mph^2 (0.4069 N/(m/s)^2)

Figure 2.69 Chevy Malibu Undergoing Dynamometer Testing

2.3.3.1.1.1 Engine Testing

The engine was removed from the vehicle and installed in an engine dynamometer test cell, as shown in Figure 2.70. The complete vehicle exhaust and emission control systems were included in the test setup. All necessary signals including the transmission input and output shaft speed signals were supplied by the test stand to prevent engine controller fault codes. The engine was fully instrumented to collect detailed performance information (e.g., exhaust/coolant temperatures, cam angles, throttle position, mass airflow).

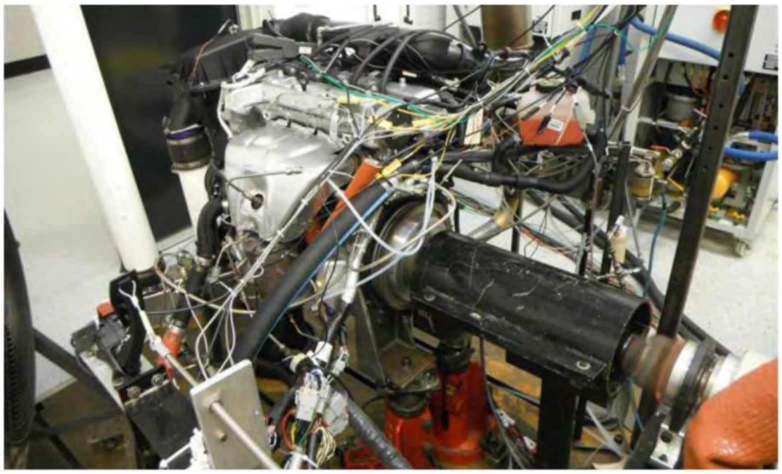


Figure 2.70 Engine Test Cell Setup

The engine fuel consumption was measured at the steady state torque and speed operating points as shown in Figure 2.71.

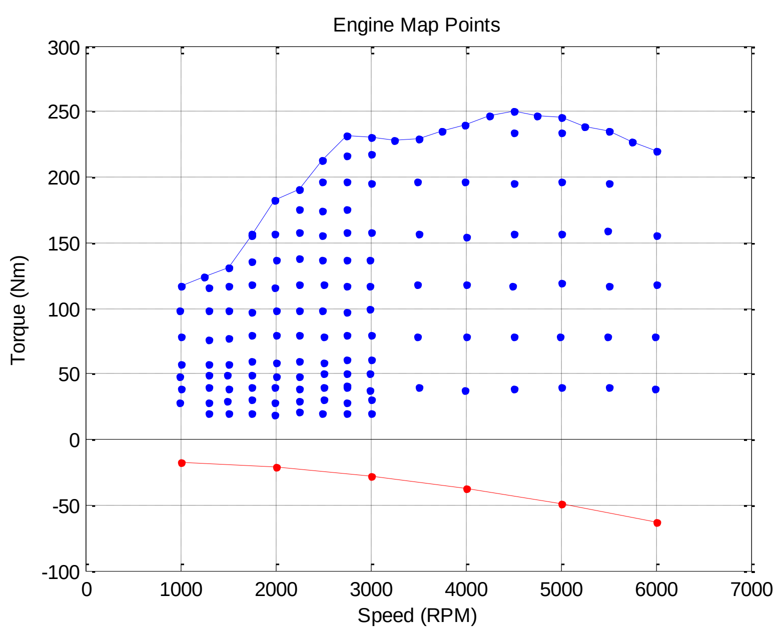


Figure 2.71 Engine Map Points

2.3.3.1.1.2 Transmission Testing

The 6-speed automatic transmission was removed from the vehicle and installed on a test stand as shown in Figure 2.72. The transmission control solenoid commands were reverse engineered and the transmission was manually controlled during testing. Transmission line pressure was externally regulated to 5 and 10 bar. Torque and speed were measured at the input of the transmission and both outputs. The input to the transmission was driven by an electric motor.

Figure 2.72 GM6T40 Transmission during Testing

The transmission losses were measured at input torques ranging from 25 to 250 Nm and input speeds ranging from 500 to 5000 RPM. For efficiency testing, the torque converter clutch was fully locked by manually overriding the clutch control solenoid. Tests were performed at two transmission oil temperatures, 37 C and 93 C, and two line pressures, 5 and 10 bar. Total efficiency for each gear during operation at 93 C, including pump and spin losses, is shown in Figure 2.73.

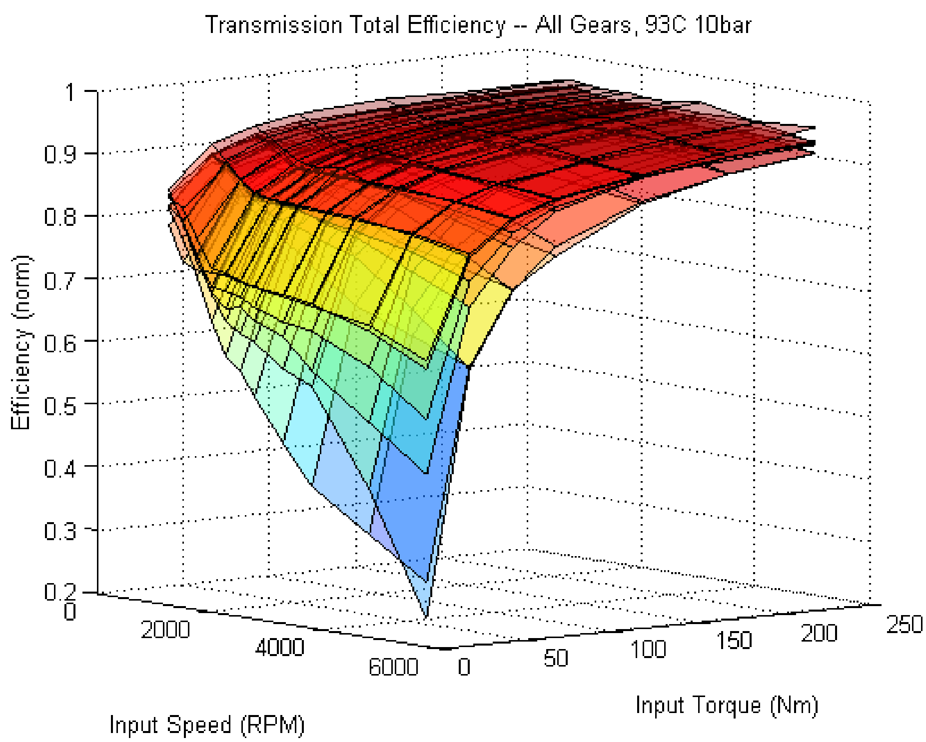


Figure 2.73 Transmission Efficiency Data at 93 C and 10 Bar Line Pressure

The torque converter was tested unlocked in 6th gear to determine speed ratio (SR), K factor[BBB] and torque ratio curves. The input speed to the transmission was held at 2000 RPM

[BBB] K-factor is approximately equal to stall_speed_rpm/square_root(stall_torque_Nm).

while decreasing the output speed to traverse the SR curve from 1.0 to 0.35 (limited due to line pressure and transmission slip). The data below SR 0.35 was extrapolated using the higher SR data. The torque converter data is shown in Figure 2.74, with the K factor curve normalized by dividing by the K factor at SR 0 (torque converter stall). Normalizing the K factor curve allows for scaling the curve up or down by multiplying by a new stall K value.

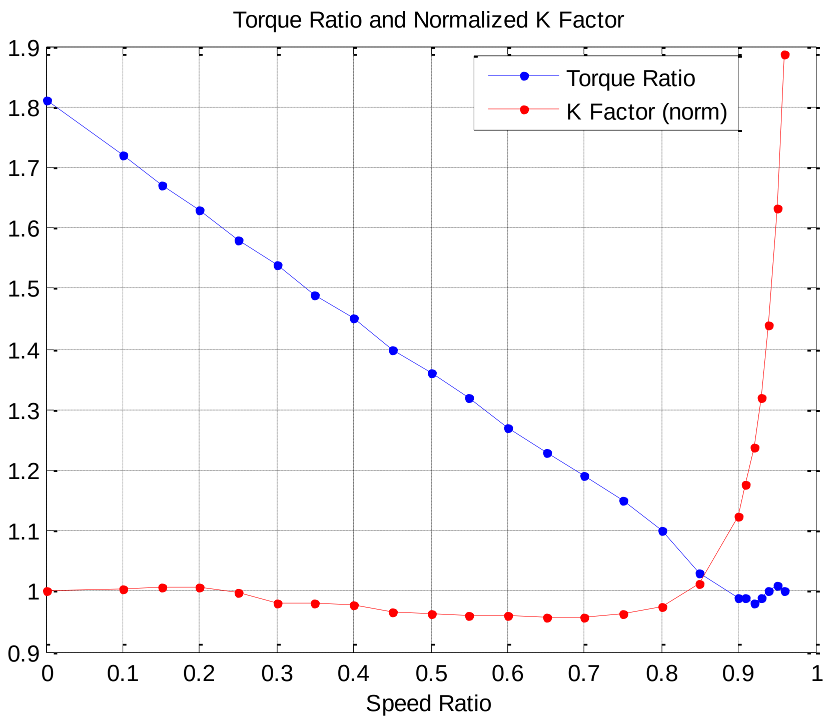


Figure 2.74 Torque Converter Torque Ratio and Normalized K Factor versus Speed Ratio

Transmission spin losses were measured in each gear with a locked torque converter and no load applied to the output shaft while varying the input speed from 500 RPM to 3000 to 5000 RPM depending on the chosen gear. Spin loss testing was performed at 5 bar and 10 bar line pressures and 37 C (cold) and 93 C (operating) oil temperatures. Figure 2.75 shows the spin loss data at 93 C for all gears and both line pressures.

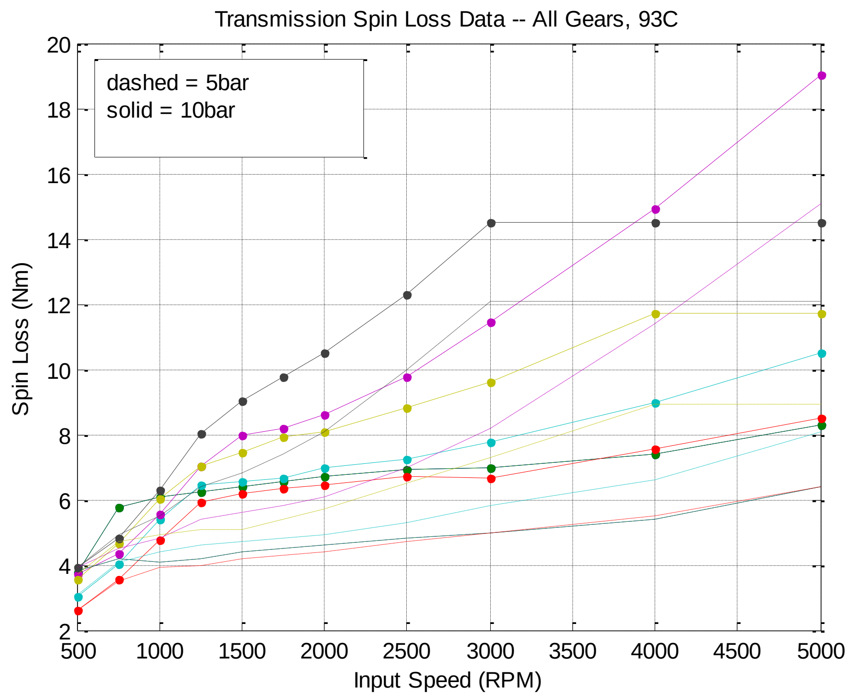


Figure 2.75 Transmission Spin Losses at 93C

2.3.3.1.2 Development of Model Inputs from Benchmarking Data

After compiling the raw data, it was necessary to adapt the data to a form suitable for use by the ALPHA model, including filling any data gaps and interpolating or extrapolating as required.

2.3.3.1.2.1 Engine Data

For use with the ALPHA model, the engine's fuel consumption map was created by converting the set of points to a rectangular surface. In addition, an estimate of the engine inertia was required since it plays a significant role in the calculation of vehicle performance and fuel economy.[538] The resulting engine data was reviewed with manufacturers prior to use in the ALPHA model.

2.3.3.1.2.2 Engine Map

Figure 2.76 shows one of the engine maps generated from the test stand data in terms of brake-specific fuel consumption (BSFC) in g/kW-hr.

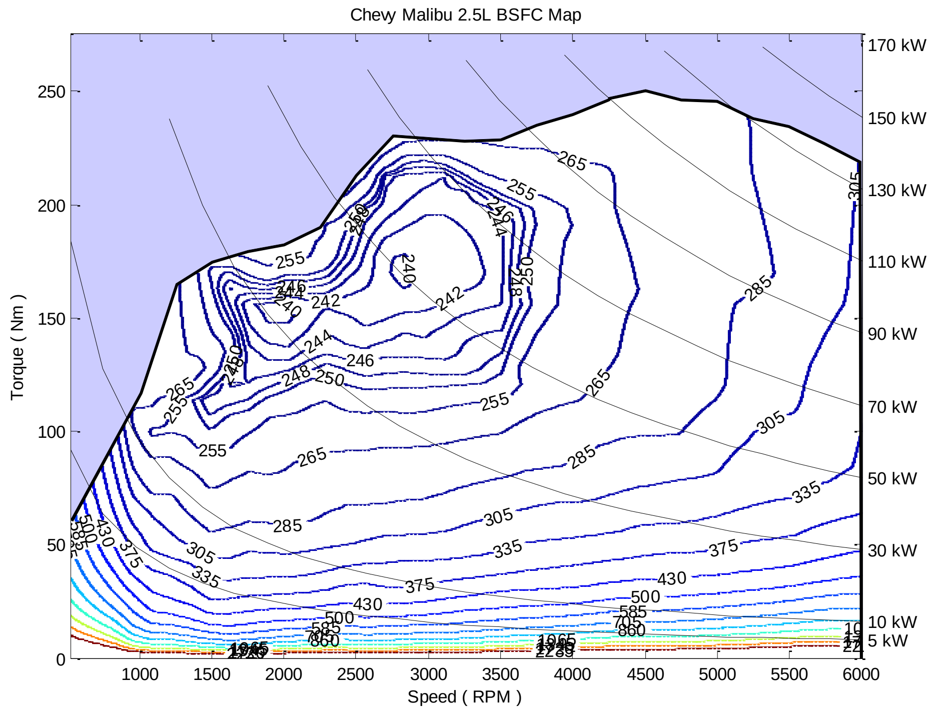


Figure 2.76 Chevy Malibu 2.5L BSFC Map

2.3.3.1.2.3 Inertia

Engine inertia plays a significant role in vehicle performance and fuel economy, particularly in the lower gears due to the high effective inertia (proportional to the square of the gear ratio) and higher acceleration rates.

To estimate the combined inertia of the engine, its attached components, and the torque converter impeller, a simple test was performed in-vehicle: the engine was accelerated with the transmission in park to the engine's maximum governed speed, then the ignition was keyed off, and the engine speed and torque were observed until the engine stopped. Engine speed and reported engine torque data (shown as negative during ignition off) were collected. The data was then run through a simple simulation and the inertia varied until the model deceleration rate reasonably matched the observed deceleration rate down to 500 RPM. Figure 2.77 shows the model result using a 0.2 kg-m^2 total inertia with the engine drag torque.

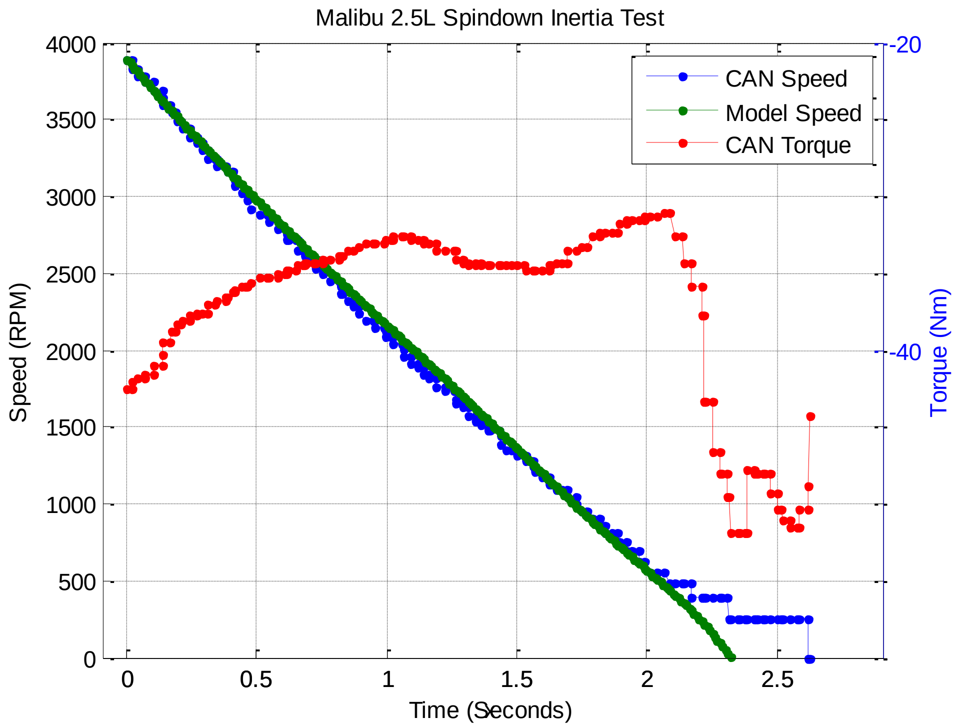


Figure 2.77 Engine Spin down Inertia Test

An oil-filled torque converter from the 2013 Malibu was weighed and measured to estimate its inertia. The weight of 12.568 kg and total diameter of 0.273 m gave an estimated 0.0585 kg-m^2 total inertia. For the purposes of modeling this inertia was then proportioned 2/3 for the impeller side and 1/3 for the turbine side based on the inertia split from other known torque converters.

Subtracting the estimated torque converter inertia results in an engine inertia (including all attached components) of approximately 0.161 kg-m^2 (0.2 – 2/3*0.0585).

The exact proportioning of the inertia makes little difference to the outcome of the model (since the total inertia is always the same) but can guide future work or estimates of component inertias.

2.3.3.1.2.4 Transmission Data

For use with the model, the total transmission efficiency data needed to be separated into gear efficiency and pump/spin torque losses. Torque converter back-drive torque ratio and K factor also needed to be calculated.

2.3.3.1.2.5 Gear Efficiency and Spin Losses

To separate the gear efficiency from the total efficiency (which includes the pump/spin losses), the total efficiency data for each gear was converted to torque loss data and the spin loss torques were subtracted. The resulting gear torque loss data was then converted to efficiency lookup tables. Some data points had to be extrapolated to cover the full speed and/or torque range. For example, first gear was only tested to 150 Nm but the full table required data up to

250 Nm. Figure 2.78 shows the estimated gear efficiencies for all gears. This process was followed for both the 37 C and 93 C data at 5 and 10 bar line pressure.

Transmission pump losses were factored out of the spin losses (as a rough approximation, since no pump loss data was available), using the lowest common spin loss to represent the pump loss.

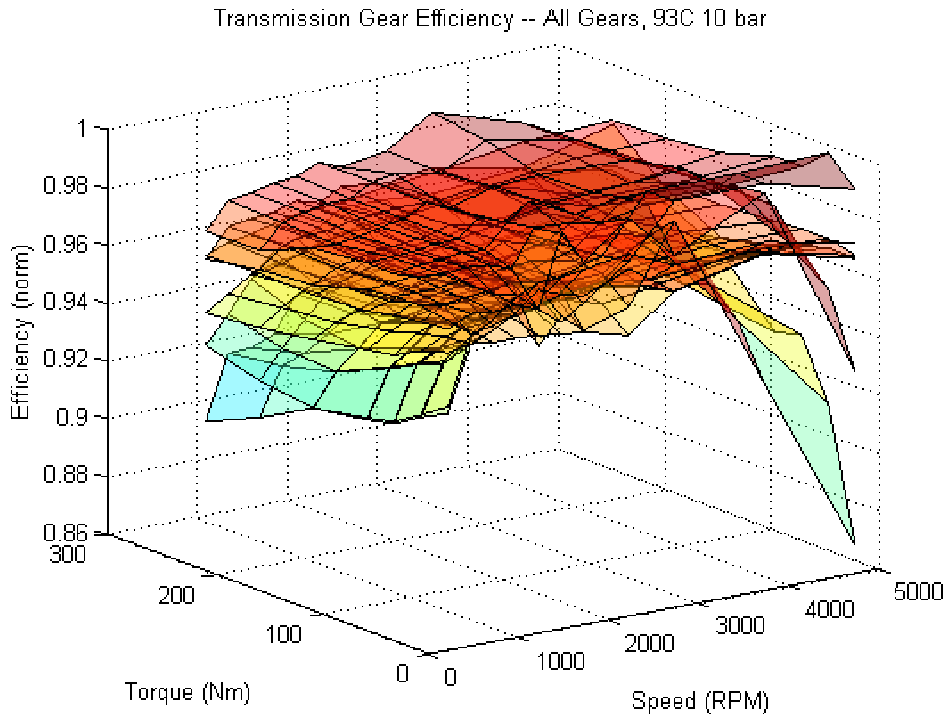


Figure 2.78 Gear Efficiency Data at 93 C and 10 bar Line Pressure

2.3.3.1.2.6 Torque Converter

To complete the model inputs for the torque converter, the torque ratio and K factor need to be calculated for the full range of speed ratios.

The torque converter back-drive torque ratio is assumed to be 0.98 for all speed ratios. The back-drive K factor is calculated from the drive K factor mirrored relative to speed ratio (SR) 1 and shifted upwards by 70 percent. The K factor at SR 1 is calculated, for modeling purposes, as 7.5 times the highest drive K factor. In practice the K factor at SR 1 is either poorly defined or near infinite so the model requires a large value but not so large as to make the solver unstable. Figure 2.79 shows the given (SR < 0.95) and calculated torque converter data.

These additional data points have little effect on the modeled fuel economy but are required for model operation and smooth transitions from positive to negative torques.

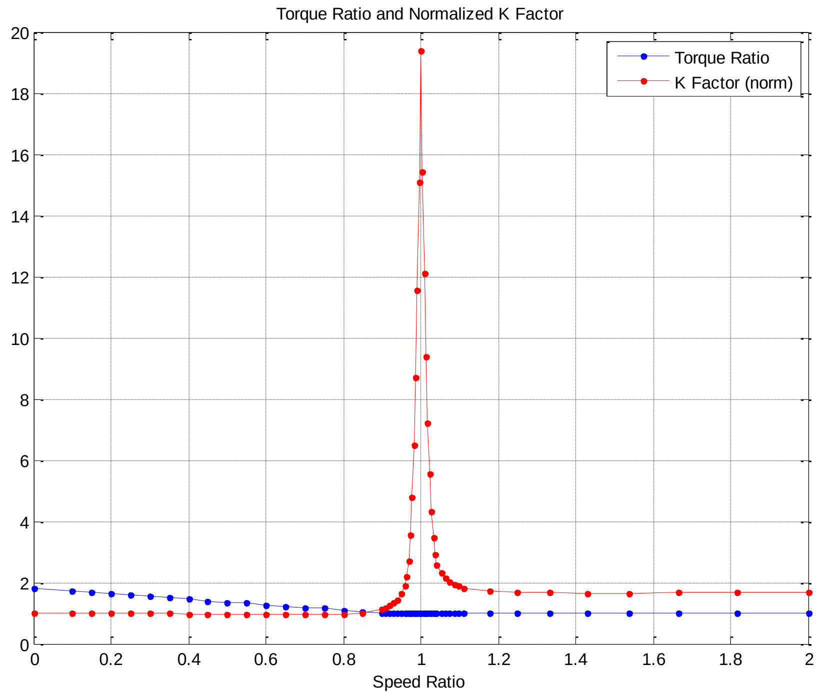


Figure 2.79 Torque Converter Drive and Back-Drive Torque Ratio and Normalized K Factor versus Speed Ratio

2.3.3.1.3 Vehicle Benchmarking Summary

Section 2.3.3.1 outlined the vehicle benchmarking process for a typical vehicle. While complex, this process yields the necessary input parameters for physics based full vehicle simulation models such as ALPHA. The following list represents the main model input parameters generated from the benchmarking process:

- Engine Maps:
  - Fuel Consumption
  - BSFC
  - Friction/Inertia
- Performance
- Transmission Maps
- Efficiency
- Torque Converter
- Shifting Strategy
- Vehicle:
  - Road Loads
  - Mechanical Loads
  - Electrical Loads

This information plus the remaining known vehicle characteristics (mass, etc.) provide the model with all of the necessary information needed for simulation. During the initial development of the ALPHA model, this complete data set from several vehicles was used to validate all of the internal calculations of the model. Once the model was validated, a wide variety of engines, transmissions, and other vehicle components were introduced to model current and future vehicles. This process is described in Section 2.3.3.2.2.

2.3.3.2 Classification of Vehicles for Effectiveness

When applying technologies in this analysis, the most representative value for effectiveness will depend on certain characteristics of each individual vehicle. As discussed in Section 2.3.1.4, the effectiveness classes in the FRM and Draft TAR were derived from vehicle size classifications defined by vehicle interior volume and gross vehicle weight rating attributes. While overall this approach placed similar vehicles together, stakeholder comments, including those from FCA, on the Draft TAR highlighted examples where some dissimilar vehicles were assigned the same technology effectiveness values. For this Proposed Determination, EPA has refined the vehicle classification approach for assigning representative effectiveness values according to the attributes of vehicle road load power and engine power-to-vehicle weight ratio as described in this section. Comments received in response to the Draft TAR from the Auto Alliance include a study by Novation Analytics, a contractor of the Auto Alliance. The report recommends (and the Alliance concurs) that EPA account for "engine displacement and vehicle load, which are first-order determinants of powertrain efficiency," [539] when determining technology effectiveness. The report further recommends the use of "displacement specific load" (i.e., the ratio of totalized vehicle load over the cycle and engine displacement) as a metric within the LPM to determine technology effectiveness.

As described in more detail in Appendix A, EPA disagrees with many of the conclusions drawn by the Alliance's contractor. However, EPA does agree that the ratio of engine size to vehicle load has a primary influence on powertrain efficiency, and thus technology effectiveness. This is because the combination of engine sizing and vehicle load affects the speed and BMEP at which the engine operates, and thus the engine operational efficiency over the test cycles. The following subsections explain the significance of engine sizing and power-to-weight ratio, and how EPA has accounted for the ratio of engine size to vehicle load in the ALPHA simulations.

2.3.3.2.1.1 Significance of Power-to-Weight Ratio and Road-Load Power Attributes

Total vehicle load consists of multiple components; chiefly inertial loads (a function of ETW over the test cycles), and aerodynamic and rolling resistance loading (together covered as "road loads"). Different combinations of road and inertial loads may lead to the same totalized vehicle load over a cycle, but different instantaneous engine operation points (and potentially different average efficiency). However, in practice, inertial loads and road loads tend to be correlated with each other and with vehicle size. Thus, it is appropriate to consider maximum-engine-power-to-ETW ratio ("power/weight ratio" as a shorthand) as a primary influence on powertrain efficiency and road-load power a secondary effect, rather than considering vehicle-load-to-engine-power ratio as a primary influence and road load to inertial load ratio as a secondary effect.

To estimate the magnitude of the effect of changing vehicle power/weight ratio on powertrain efficiency and technology effectiveness, EPA used its ALPHA full vehicle simulation model to determine changes in CO_2 emissions when different size engines were incorporated into a standard vehicle. Recognizing that changing engine size also affects vehicle performance, ALPHA was also used to simulate acceleration times. Finally, to examine effectiveness (i.e., the change in CO_2 when advanced technology is implemented), the same power/weight ratio study was performed with powertrains containing different technologies.

The baseline vehicle modeled was a standard car (similar to a 2008 Toyota Camry), with a 159 HP PFI engine, five-speed transmission, Camry road loads, and 3500 pound ETW. CO_2 emissions over the FTP and HWFET cycles and acceleration times were simulated within ALPHA. The results for this simulation were two-cycle combined CO_2 emissions of 282 g/mile, an estimated 0-60 time of 8.05 seconds, and a "performance sum" of 0-60, 30-50, 50-70, and 1/4-mile times of 35.5 seconds (see Section 2.3.1.2).

The engine efficiency in this particular simulation is represented in Figure 2.80. The figure shows a two-cycle engine “heat map” from the standard car simulation, plotting the speeds and torques where the engine operates over the FTP and HWFET on an engine efficiency map. Points where the engine spends more operational time are plotted in red, points where it spends less time are plotted in cooler colors (blue, green), and points where there is no engine operation remain white. The pink line is the line of best efficiency at each power.

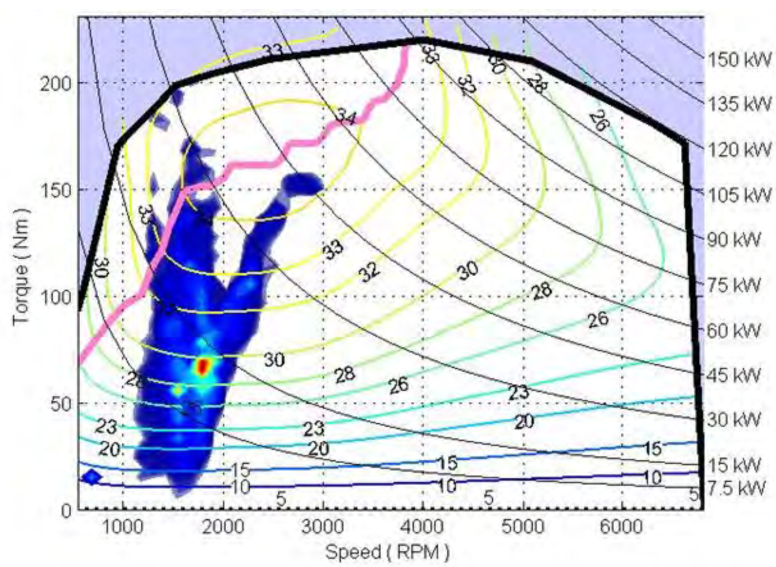


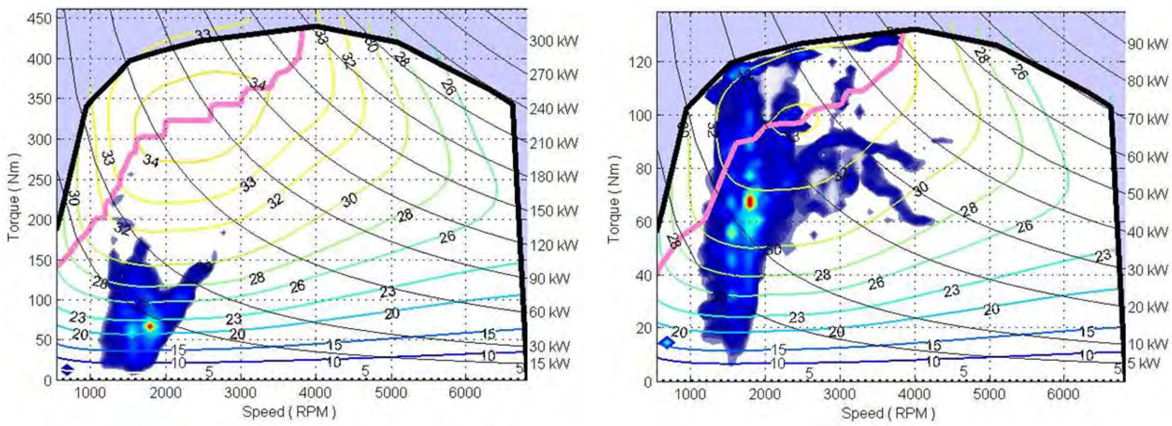
Figure 2.80 Engine “heat map” for baseline vehicle, showing engine operation over the FTP and HWFET.

Figure 2.80 shows a red “hot spot” of engine operation near 70 Nm, with extended operation down to 15-20 Nm and up to 150 Nm. Almost the entire operational range occurs at torques lower than the line of best efficiency. This represents a somewhat “typical” vehicle, where two-cycle engine operation and engine efficiency are not well matched.

2.3.3.2.1.2 Effect of Changing Power-to-Weight Ratio

To examine the effect of the performance-fuel economy tradeoff, the baseline case was altered by changing the engine size (and thus maximum power) in 2 percent increments from 60 percent to 200 percent of the baseline case, which resulted in maximum engine horsepower ranging from about 100 HP to about 300 HP. Other vehicle characteristics (including ETW) were held constant, resulting in a maximum-engine-power-to-ETW ranging from about 0.03 HP/lb to about 0.09 HP/lb. For vehicles with each engine size, performance metrics and CO_2 emissions over the FTP and HWFET cycles were simulated using ALPHA as in the baseline case.

As an example of the effect of varying engine size (i.e., varying power/weight ratio), Figure 2.81 shows two-cycle engine "heat maps" for both a very high power/weight ratio vehicle (0.09 HP/lb) with a large engine, and a very low power/weight ratio vehicle (0.03 HP/lb) with a small engine. In both cases, the operational combinations of speed and torque are approximately the same as shown in the baseline case in Figure 2.80 (note the red hot spot at about 70 Nm on all three heat maps). This is because the required speed and torque are driven by the vehicle weight and road loads, which in this simulation remain identical. However, the peak torque of the large engine is about 440 Nm, and the small engine only 132 Nm, and thus the larger engine operates in much lower BMEP areas of the map.



(a) High power/weight ratio (~0.09 HP/lb) **(b) Low power/weight ratio (~0.03 HP/lb)**

Figure 2.81 Two-cycle heat maps for two different power/weight ratio vehicles.

The difference in operation means that the high power/weight ratio vehicle operates much farther from the line of best efficiency (the pink line in Figure 2.81). Conversely, the low power/weight ratio vehicle operates closer to the line of best efficiency; in other words, the smaller engine is better matched to the efficiency "sweet spot." Although these graphs were generated by changing engine size only, in general the match between engine efficiency and operation is a function of the ratio between engine size and vehicle loads. Engine map operation area of vehicles with similar power/weight ratios would be expected to be very similar, regardless of absolute scale.

The effect of this engine matching on CO_2 emissions and vehicle acceleration performance is illustrated in Figure 2.82, which shows the trends in combined cycle CO_2 emissions and the "performance time sum" of 0-60, 30-50, 50-70, and 1/4-mile acceleration times as a function of power/weight ratio. Although this performance time sum was chosen for reasons detailed in Section 2.3.1.2, other performance metrics show a similar trend to that exhibited in Figure 2.82.

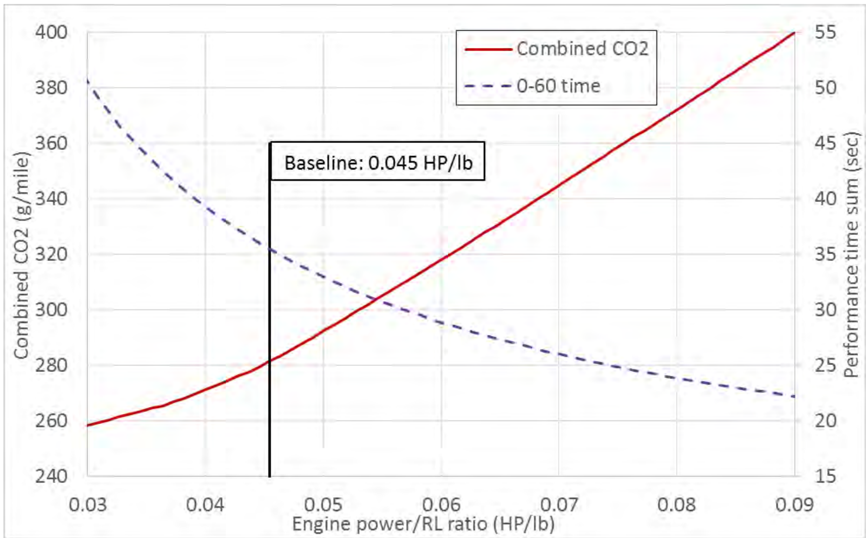


Figure 2.82 CO_2 and performance time sum as a function of power/weight ratio.

As power/weight ratio increases, acceleration times decrease and CO_2 emissions increase, as would be expected from the heat maps depicted in Figure 2.81. The trends in both CO_2 emissions and acceleration performance are monotonic over the range of power/weight ratios shown. As such, the acceleration times and combined cycle CO_2 emissions in Figure 2.82 can be directly compared, as shown in Figure 2.83, to create a "trade-off" curve, demonstrating how engine power (i.e., displacement) can be altered to increase performance at the expense of fuel economy, or to increase fuel economy at the expense of performance. More advanced technology powertrains would be expected to move the curve closer to the origin, as noted by the arrow.

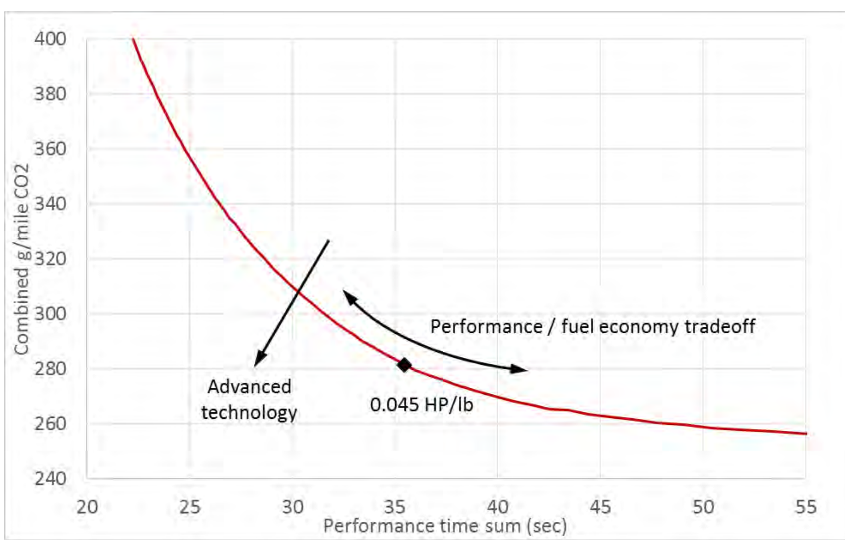


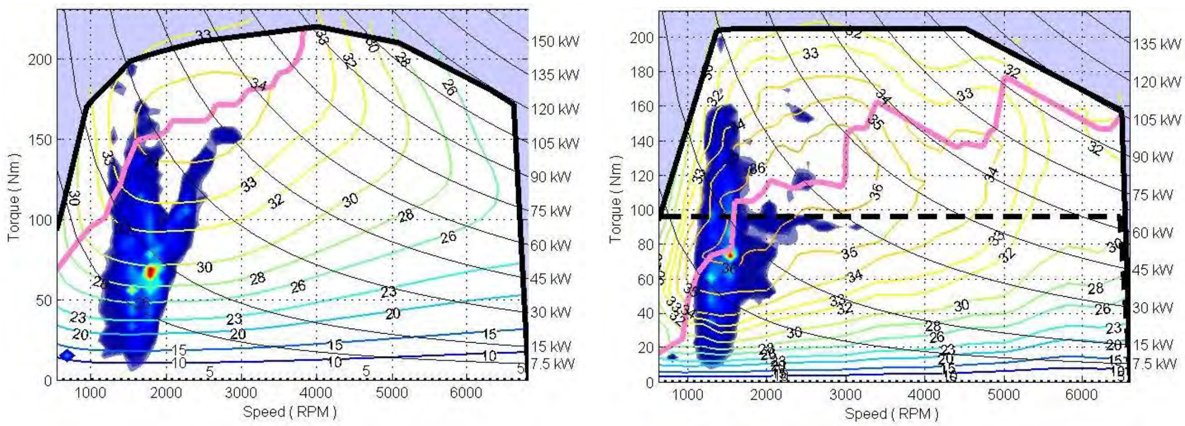
Figure 2.83 CO_2 as a function of acceleration performance time sum.

2.3.3.2.1.3 Effect of Advanced Technologies

More advanced technologies produce lower CO_2 for the same performance, and so would be expected to move the trade-off curve shown in Figure 2.83 closer to the origin, reducing CO_2

emissions, acceleration time, or both. To explore this, ALPHA simulations were run using different powertrains, but the same vehicle road and inertia loads as before. The powertrains simulated were a 2013 GDI engine (similar to that found in the 2013 Chevrolet Malibu) paired with a six-speed transmission, and a 24-bar turbo downsized engine (as modeled by Ricardo and included in the FRM) paired with an eight-speed transmission. Two-cycle CO_2 emissions and acceleration performance were calculated.

Figure 2.84 compares the heat map for the nominally sized PFI engine with 5-speed transmission (identical to the simulation result shown in Figure 2.80) with the future 24-bar turbo downsized engine paired with an eight-speed transmission. The powertrains are sized to have similar acceleration performance, and thus have slightly different maximum power ratings.

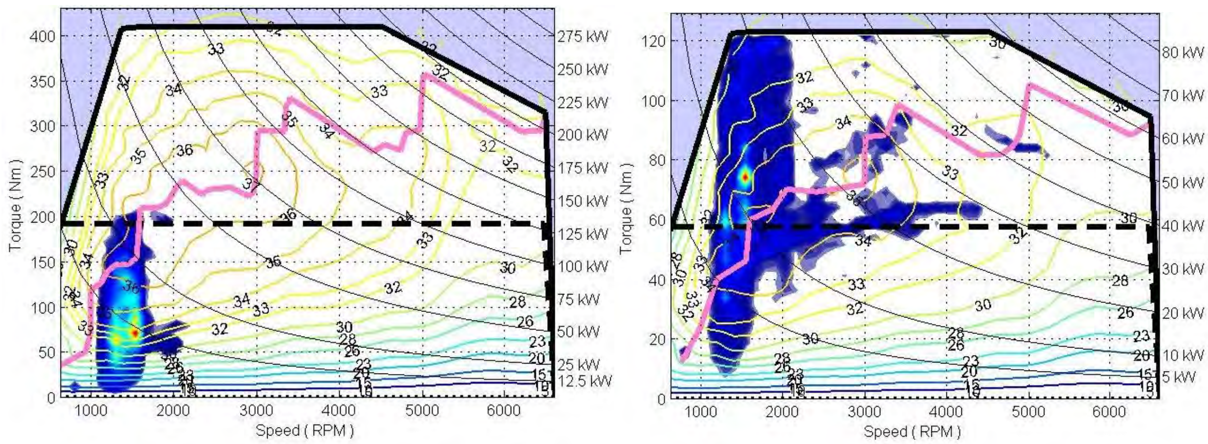


(a) PFI engine heat map (shown in Figure 2.80) **(b) 24 bar turbo downsized engine heat map**

Figure 2.84 Engine Heat maps for the baseline PFI engine and a 24-bar turbo downsized engine

The future 24-bar turbo downsized engine has a higher peak efficiency (over 36 percent compared to over 34 percent), which contributes to a higher effectiveness. In addition, it also has a peak efficiency zone that extends to lower speeds and loads than that in the PFI engine. The lower peak efficiency zone results in a better match between vehicle loading and powertrain efficiency. In particular, the PFI engine has a hot spot which is substantially lower than the line of highest efficiency, while the turbo downsized engine has a hot spot located almost directly on the line of highest efficiency.

The quality of the match between powertrain efficiency and vehicle road load is a function of vehicle power/weight ratio. To investigate this effect, engine sizes for the GDI and TDS engines were again swept in 2 percent increments, and two-cycle CO_2 emissions and acceleration performance were simulated. Engine heat maps for high and low power/weight ratio turbo downsized powertrains (roughly equivalent in acceleration performance to the PFI powertrains illustrated in Figure 2.83) are shown in Figure 2.85.



(a) High power/weight ratio **(b) Low power/weight ratio**

Figure 2.85 Engine operation heat maps for the turbo downsized engine with eight-speed transmission.

As expected, the shape and extent of the heat maps in Figure 6 are roughly equivalent with respect to speed and torque, but the low power/weight ratio engine operates at higher BMEP. However, unlike the PFI powertrains, the low power/weight ratio powertrain has a hot spot that is above the line of best efficiency, indicating that the match between vehicle and powertrain for the smaller engine is no better (and may actually be worse) than that of the nominally sized powertrain shown in Figure 2.84.

2.3.3.2.1.4 Advanced Technology Trade-Off Curves

The relocation of the peak engine efficiency means that not only do these advanced powertrains have a trade-off curve that is closer to the origin than the one shown for the PFI engine in Figure 2.83, but these curves also have a different slope, as shown in Figure 2.86, where the "tradeoff curves" for the advanced technologies are progressively flatter than for the PFI engine. These trade-off curves are presented as a function of acceleration times rather than power/weight ratio so that the resulting comparisons are performance neutral.

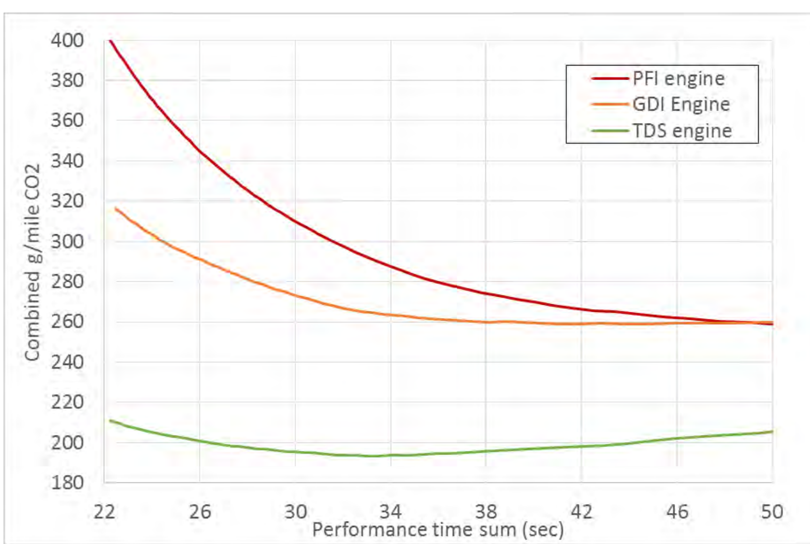


Figure 2.86 CO_2 as a function of performance time sum for PFI, GDI, and turbo downsized engines.

The variation in slope of the lines in Figure 2.86 suggests two things. First, the more advanced technologies have flatter curves, with the most advanced technology (the 24 bar turbo downsized engine) even exhibiting a point of minimum CO_2 emissions. Although this simplified ALPHA analysis does not include real-world effects such as the additional mass associated with larger engines, this trend is still likely to hold in the vehicle fleet, as the changes in engine maps and powertrain matching due to the implementation of advanced technology still fundamentally alter the relationship between engine size and CO_2 emissions.

A study by Novation Analytics, commissioned by the Auto Alliance and included with its comments on the Draft TAR, supports this conclusion. Using a simulation of turbo downsized engines, they state, "where a powertrain is already operating at a high specific load [i.e., in a low power/weight ratio vehicle], further downsizing may offer little benefit as both scenarios are already operating in the high efficiency region where the relative gains from a further increase in specific load (via smaller displacement) are minimal."[540]

Therefore, the relationship between CO_2 emissions and acceleration performance can vary substantially as more advanced technology is implemented. Consequently, any tradeoff relationship between these factors developed using less advanced technology engines (such as the PFI engine curve in red in Figure 2.86) should not be expected to hold when more advanced technology is implemented. To the contrary, increasing performance using advanced engines should have a much decreased effect on fuel consumption when compared to less advanced engines.

In addition, Figure 2.86 shows that the potential reduction in CO_2 emissions from advanced technology powertrains is a function of vehicle performance, and thus power/weight ratio. Visually, it can be seen that the combined CO_2 emissions reduction from the GDI engine (orange line) compared to the PFI engine (red line) clearly varies from around 20 percent with higher performance vehicles to nearly 0 percent in lower performance vehicles.

There is also a difference in CO_2 reduction between the GDI engine and the turbo downsized engine (the green line in Figure 2.86). This difference is calculated in Figure 2.87, which shows the reductions in CO_2 emissions obtainable from the 24 bar turbo downsized engine with eight-speed transmission, compared to that of a GDI engine with six-speed transmission having similar acceleration performance. The comparisons between powertrains are done on a performance neutral basis, matching vehicles with the same acceleration performance time sum, and so reductions in CO_2 are shown as a function of performance time sum. Approximate power/weight ratio is also given in the figure as a reference.

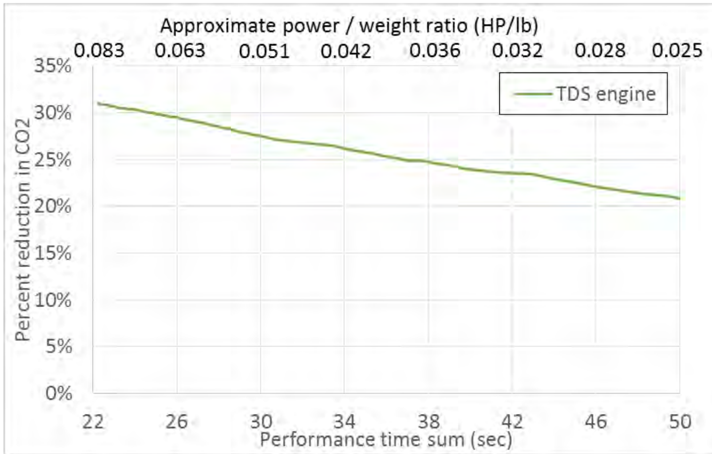


Figure 2.87 Reduction in CO_2, comparing a turbo downsized engine to a GDI engine with similar acceleration performance.

As seen in Figure 2.87, the potential percent reduction in CO_2 emissions is a function of performance (and thus the vehicle power/weight ratio), where vehicles with relatively small engines (on the right hand side of Figure 2.87) have less potential reduction than vehicles with relatively large engines (on the left hand side of Figure 2.87). Across the relatively wide range of power/weight ratios shown in Figure 2.87, this change in effectiveness is quite substantial.

This study shows that advanced technology engines change the match between engine efficiency and engine operation (as shown in Figure 2.84). Because this match is also affected by vehicle loading, the ratio of engine size to vehicle load (i.e., the vehicle power/weight ratio) is a primary influence on powertrain efficiency and technology effectiveness. Additionally, and for the same basic reason, the tradeoff between CO_2 emissions and performance changes as advanced technology is introduced, with more advanced technology packages generally tending to have flatter tradeoff curves.

2.3.3.2.2 Definition of Effectiveness Classes

Because technology effectiveness is clearly related to engine operation through power-to-weight ratio, EPA agrees with the Auto Alliance that calculation of technology effectiveness values should be tied to engine power and vehicle loads. Because total vehicle load is composed of both inertial load and road loads (primarily tire rolling and aerodynamic loading), which are only loosely correlated, EPA has looked at vehicle loads two-dimensionally, through both power-to-weight ratio and road load horsepower.

For this Proposed Determination EPA has revised the classification approach used for applying effectiveness values from the size-based classification used in the FRM and Draft TAR to an approach that is based on vehicle power-to-weight and road load characteristics. Each vehicle in the MY2015 baseline fleet has been assigned to one of the ALPHA classes shown in Table 2.32 using the procedure described in this Section.

In the first step, because vehicles with high capacity for towing and hauling have road load and power-to-weight characteristics that are fundamentally different from other passenger vehicles, vehicles defined as 'pickup trucks' under 40 CFR § 600.315-08 were assigned to the 'Truck' ALPHA class. The remaining vehicles were divided into low, medium, and high power-to-weight levels using the MY2015 production volume proportions defined in Figure 2.88. The production volumes for plug-in vehicles (PHEVs and BEVs) were not included in the percentile calculations for power-to-weight ratios.

Next, the distribution of road load horsepower values was investigated within each of these power-to-weight categories. As can be seen in Figure 2.89, both the 'low' and 'mid' power-to-weight categories exhibit bimodal distributions, with vehicles clustered in two groups below and above the median values of road load horsepower. The vehicles that comprise these two groups tend to correspond to cars having lower road loads, and sport-utility vehicles and vans and having higher road loads. However, there are some examples where vehicles in different market segments are now classified together. This is appropriate, since for example a sedan with a large frontal area and high tire rolling resistance would tend to have technology effectiveness benefits more like a cross-over utility vehicle than like other cars. In recognition of the relatively broad and bimodal distributions of road load horsepower, these two power-to-weight categories are further subdivided into 'low' and 'high' road load horsepower levels as shown in Table 2.46.

Table 2.46 Criteria for Classifying Vehicles by Power-to Weight ratio and Road Load Horsepower

Power-to-Weight				Road Load Horsepower at 50mph			
Level	Percentile Range	Cutoff Values (hp/lb ETW)		Level	Percentile Range	Cutoff Values (hp)	
		Lower	Upper			Lower	Upper
Low	0 to 40	-	0.049	Low	0 to 50	-	11.8
				High	50 to 100	11.8	-
Mid	40 to 80	0.049	0.061	Low	0 to 50	-	14.0
				High	50 to 100	14.0	-
High	80 to 100	0.061	-	-	-	-	-

Note: Power-to-Weight percentiles are production volume-based after excluding PEVs and pickup trucks. Road Load Horsepower percentiles are defined within 'Low' and 'Mid' Power-to-Weight groups.

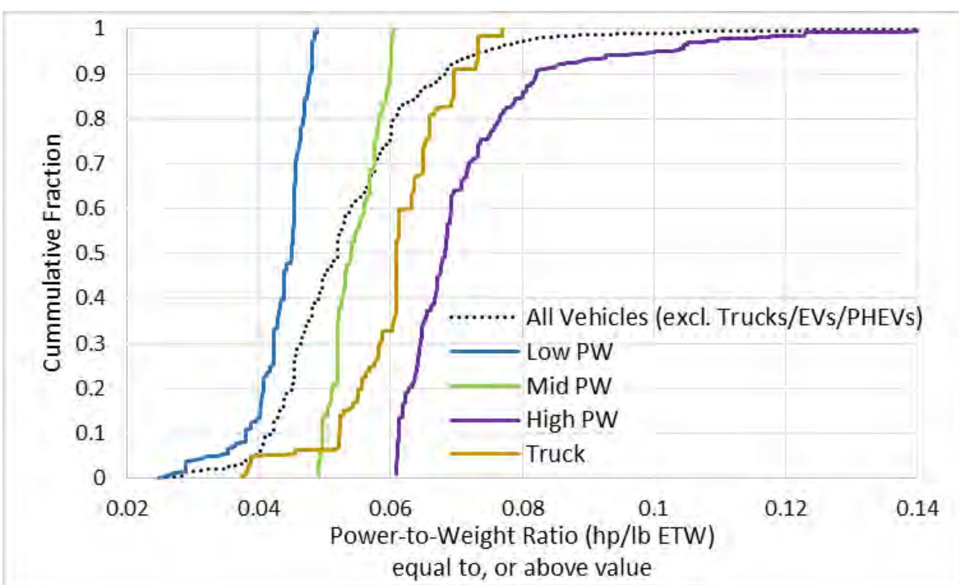


Figure 2.88 Production Volume Distribution of Power-to-Weight Ratios in MY2015 Fleet

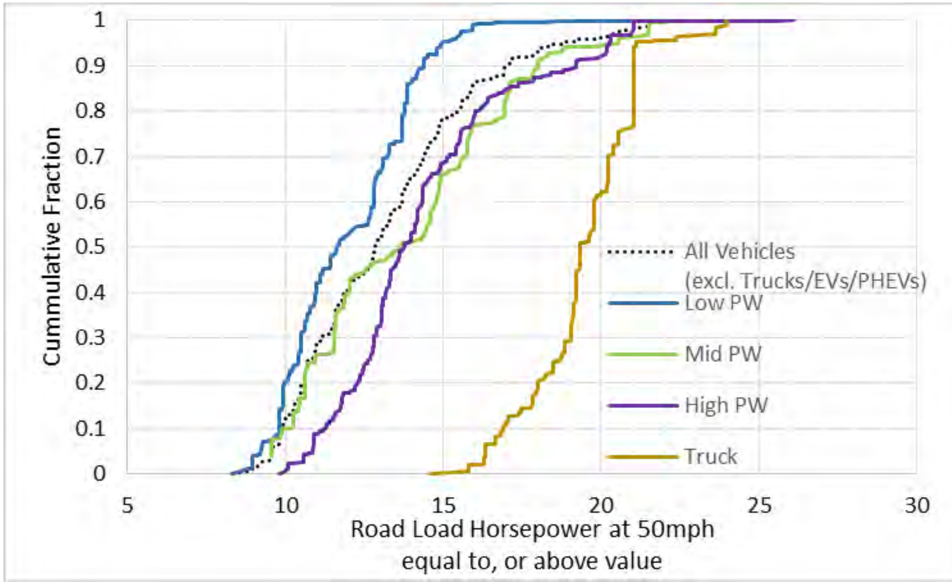


Figure 2.89 Production Volume Distribution of Road Load Horsepower at 50mph in MY2015 Fleet

The six vehicle classes that result from the process described above are shown in Table 2.47 along with the important production volume-weighted average characteristics that exemplify the power-to-weight and road load characteristics of each class. These values define an exemplar vehicle for each of the classes, referred to interchangeably as an 'ALPHA Class' or 'Effectiveness Class', the characteristics for each of which are used in the ALPHA model as described in Section 2.3.3 for the purpose of developing representative effectiveness values of technologies added to vehicles in the MY2015 baseline fleet.

Table 2.47 Characteristics of Exemplar Vehicles for the Six ALPHA Classes

ALPHA Class	Abbreviation	Engine Rated Power (hp)	A coeff. (lbf)	B coeff. (lbf/mph)	C coeff. (lbf/mph2)	ETW (lbs)
Low Power-to-Weight, Low Road Load	LPW_LRL	137.5	26.56	0.0630	0.01879	3257
Mid Power-to-Weight, Low Road Load	MPW_LRL	191.1	32.27	0.0754	0.01993	3626
High Power-to-Weight	HPW	313.8	35.76	0.3414	0.02086	4401
Low Power-to-Weight, High Road Load	LPW_HRL	172.4	34.95	0.0875	0.02526	3855
Mid Power-to-Weight, High Road Load	MPW_HRL	275.2	39.30	0.3348	0.02721	4849
Truck	Truck	324.2	39.62	0.4641	0.03222	5303

2.3.3.2.3 *Comparison to Draft TAR Classification Approach and Exemplar Vehicles*

The power, weight, and road load attributes assumed for effectiveness modeling in the FRM and Draft TAR were based on the characteristics of six typical, actual vehicles from the MY2007 to MY2010 time frame. While these assumptions were appropriate for the previous analyses, the approach used for this determination results in exemplar vehicles with characteristics that are more representative of vehicles in the fleet in MY2015. In particular, as shown in Table 2.48, the power-to-weight ratios of the exemplar vehicles for this Proposed Determination are up to 20 percent higher than the corresponding vehicle classes in the Draft TAR, consistent with the increases in engine power that have occurred over recent redesign cycles for many vehicles. In addition, the slight road load horsepower decreases for four of the six classes is likely the result of improvements in vehicle design such as improved aerodynamics.

Table 2.48 Change in Power-to-Weight and Road Load Horsepower of Exemplar Vehicles Relative to Draft TAR

Changes in Exemplars for Proposed Determination relative to Draft TAR			Draft TAR Exemplar Vehicles (for reference only)					
ALPHA Class*	Change in Road Load Horsepower at 50mph	Change in Power-to-Weight Ratio	Vehicle Class	Engine Rated Power	A coeff. (lbf)	B coeff. (lbf/mph)	C coeff. (lbf/mph2)	ETW (lbs)
LPW_LRL	-5.8%	+1.0%	Small Car	109.7	24.68	0.1426	0.01984	2625
MPW_LRL	+1.1%	+19.0%	Standard Car	158.2	29.80	0.1721	0.01860	3571
HPW	-5.1%	+14.2%	Large Car	249.8	45.20	0.2409	0.02135	4000
LPW_HRL	-9.8%	+4.1%	Small MPV	171.8	27.64	0.4729	0.02493	4000
MPW_HRL	+2.6%	+22.8%	Large MPV	208.0	32.43	0.4873	0.02566	4500
Truck	-15.5%	+18.0%	Truck	306.2	48.84	0.6104	0.03614	5911

*Note: The ALPHA Classes defined for this Proposed Determination are not intended to correspond one-to-one with the Draft TAR, but are presented here to show the general trends in power-to-weight and road load horsepower.

In public comments, FCA cited examples from the Draft TAR where dissimilar vehicles were assigned the same benefits, commenting that "...the Fiat 500 Turbo and the V6 Chrysler 300 AWD are assigned the same benefits for every technology. This is inappropriate given the vehicle size, engine size, and drivetrain difference between them" (p. 35, FCA comments). EPA has refined the ALPHA classifications for this Proposed Determination with the goal of minimizing the variation within each class, particularly for the parameters of power-to-weight and road load power. While EPA recognizes that the examples provided by the commenter were meant to be simply illustrative, we note that using this revised vehicle classification approach, the MY2015 Fiat 500 Turbo and V6 Chrysler 300 are now assigned to different ALPHA classes for this Proposed Determination (MPW_LRL and HPW, respectively.) More broadly, because vehicles are now grouped using engine and vehicle road load characteristics, and each class contains roughly equal sales-weighted volumes of vehicles, there will be a smaller range of effectiveness values within each class. Furthermore, because the exemplar vehicles have been updated to represent the sales-weighted average of characteristics within each ALPHA class, there is a better match between the vehicles in the class and the associated exemplar.

In addition, in response to public comment, the effectiveness values calculated for each vehicle for the final OMEGA runs were adjusted according to the vehicle's power to weight ratio. For each vehicle classification, a set of effectiveness adjustment factors within ALPHA was calculated by sweeping engine power for each technology. From these results, a linear adjustment factor was calculated for each class and each technology. See Figure 2.23 for an example, in this case the MPW_HRL class, and Section 2.3.3.5.4 for adjustment parameters for all ALPHA classes.

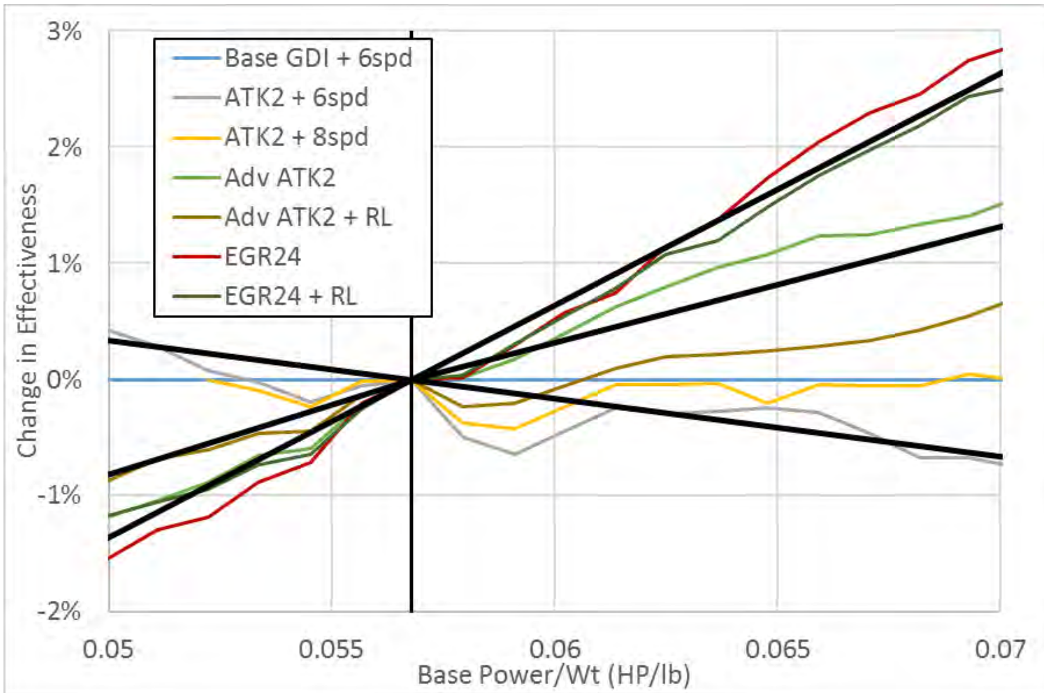


Figure 2.90 MPW_HRL Class Effectiveness Change as a Function of Power-to-Weight Ratio

As shown in Table 2.49 and Figure 2.91, the range of power-to-weight values within the high and mid power-to-weight groups, in particular, is significantly smaller using the updated classification approach. As can also be seen in Figure 2.91, the Draft TAR exemplar values for power-to-weight, while appropriate for the FRM analysis conducted in 2012, are now generally one standard deviation or more below the production-weighted average of the MY2015 fleet.

Table 2.49 MY2015 Summary Statistics of Power-to-Weight Ratio Using Draft TAR and Proposed Determination Classification Approaches

Power-to-Weight Ratio (100xhp/lb)									
PD Classification Approach					Draft TAR Classification Approach				
ALHPA Class	Median	Std. Dev.	min-max	N	Vehicle Class	Median	Std. Dev.	min-max	N
LPW_LRL	4.22	0.53	2.62-4.86	3,059,319	Small Car	4.15	0.71	2.62-6.40	833,737
MPW_LRL	5.27	0.26	4.80-6.07	3,027,591	Standard Car	5.27	1.13	2.70-13.10	6,627,852
HPW	7.14	1.34	5.31-17.50	2,979,046	Large Car	9.35	2.18	4.80-17.50	394,688
LPW_HRL	4.48	0.27	2.49-4.98	2,859,184	Small MPV	4.59	0.29	2.49-5.26	2,711,222
MPW_HRL	5.69	0.33	4.90-6.29	2,896,808	Large MPV	5.84	0.66	3.65-10.31	4,334,273
Truck	6.28	0.95	3.74-8.56	1,786,224	Truck	6.39	0.84	3.83-8.56	1,706,401

Note: The ALPHA Classes defined for this Proposed Determination are not intended to correspond one-to-one with the classes used in the Draft TAR, but are presented here to show the effect of the updated classification approach.

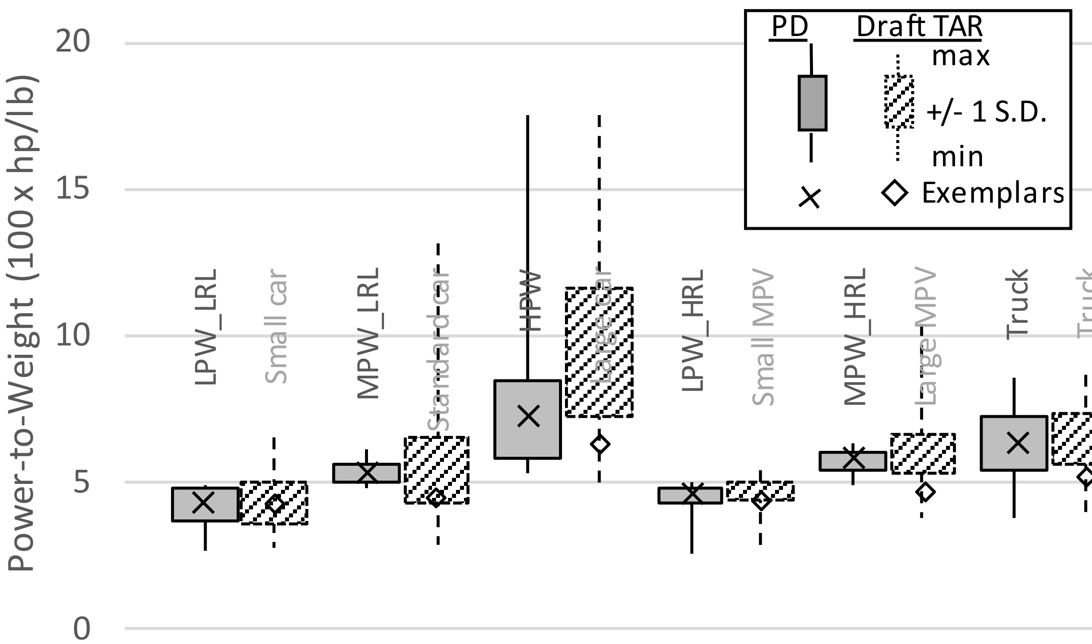


Figure 2.91 MY2015 Production-weighted Distributions of Power-to-Weight Ratio Using Draft TAR and Proposed Determination Classification Approaches

As can be seen in Figure 2.92, the updated exemplars for this Proposed Determination are representative of the average MY2015 vehicle's road load horsepower in each class. In comparison, the Draft TAR exemplar road load horsepower values tend to be higher than typical MY2015 vehicles. Table 2.50 and Figure 2.92 show that the range of road load horsepower values within each class is largely unchanged by updating the classification approach from the Draft TAR to this Proposed Determination. One exception is the high power-to-weight class, which has a greater range of road load horsepower values with the updated approach. While a narrower range of road load horsepower values is preferable to a larger one, when defining the classes EPA gave priority to minimizing within-class variation in power-to-weight ratio due to the dominate influence that attribute has on effectiveness values. Overall, the road load horsepower values in all classes, including the high power-to-weight class, are represented fairly by the appropriate exemplar values.

Table 2.50 MY2015 Summary Statistics of Road Load Horsepower Using Draft TAR and Proposed Determination Classification Approaches

Road Load Horsepower at 50mph									
PD Classification Approach					Draft TAR Classification Approach				
ALHPA Class	Avg.	Std. Dev.	min-max	N	Vehicle Class	Avg.	Std. Dev.	min-max	N
LPW_LRL	10.3	0.8	8.3-11.7	3,059,319	Small Car	10.1	1.0	8.3-13.8	833,737
MPW_LRL	11.1	1.3	9.3-14.6	3,027,591	Standard Car	11.1	1.4	8.7-19.2	6,627,852
HPW	14.2	2.7	9.8-26.1	2,979,046	Large Car	13.6	1.1	10.8-19.5	394,688
LPW_HRL	13.6	1.1	10.6-23.8	2,859,184	Small MPV	13.6	1.1	11.4-17.9	2,711,222
MPW_HRL	16.4	1.9	13.9-22.6	2,896,808	Large MPV	16.3	2.2	11.3-26.1	4,334,273
Truck	19.3	1.8	14.6-25.8	1,786,224	Truck	19.5	1.7	16.1-25.8	1,706,401

Note: The ALPHA Classes defined for this Proposed Determination are not intended to correspond one-to-one with the classes used in the Draft TAR, but are presented here to show the effect of the updated classification approach.

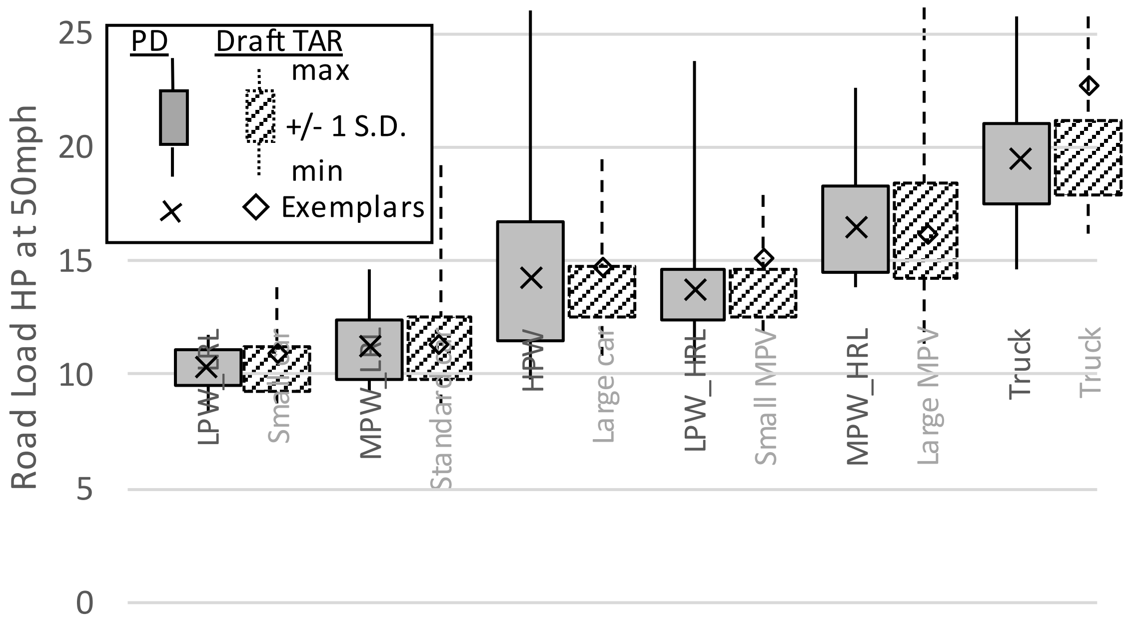


Figure 2.92 MY2015 Production-weighted Distributions of Road Load Horsepower Using Draft TAR and Proposed Determination Classification Approaches

2.3.3.3 ALPHA Vehicle Simulation Model

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to evaluate the Greenhouse Gas (GHG) emissions of Light-Duty (LD) vehicles. In order to have additional flexibilities and transparency, EPA developed an in-house full vehicle simulation model that could freely be released to the public. Model development, along with the data collection and benchmarking that comes along with model calibration, is an extremely effective means of developing expertise and deeper understanding of technologies and their interactions. Better understanding of technologies makes for more robust regulatory analysis. Having a model available in-house allows EPA to make rapid modifications as new data is collected.

Throughout this section of the TSD, EPA has provided details on the major technology assumptions built into ALPHA. EPA has also provided technical details in the Docket describing the process used to build the fuel consumption maps for six of the engines mentioned in this TSD, as well as data maps for two transmissions.[541] In the time since the 2012 FRM, EPA has published over 15 peer-reviewed papers describing results of key testing, validation and analyses.

EPA began developing both light-and heavy-duty vehicle simulations simultaneously as these vehicles share many of the same basic components. The light-duty vehicle model (ALPHA), and the heavy-duty model (GEM), share the same basic architecture.[CCC]

EPA has validated the ALPHA model using several sources including vehicle benchmarking,[538] stakeholder data, and industry literature. While the ALPHA model continues to be refined and calibrated, the version in use as of April 26, 2016 was externally peer reviewed.[542] To further enhance transparency, in May 2016, EPA published on the EPA website the specific version of the ALPHA model that was reviewed. This package included the peer review input data and runnable MatLab Simulink source code.

2.3.3.3.1 *General ALPHA Description*

ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior. The software tool is a MATLAB/Simulink based simulation.

Within ALPHA, an individual vehicle is defined by specifying the appropriate vehicle road loading (inertia weight and coast-down coefficients) and specifications of the powertrain components. Powertrain components (such as engines or transmissions) are individually parameterized and can be exchanged within the model.

Vehicle control strategies are also modeled, including engine accessory loading, decel fuel shutoff, hybrid behavior, torque converter lockup, and transmission shift strategy. Transmission shifting is parameterized and controlled by ALPHAshift,[543] a shifting strategy algorithm that ensures an appropriate shifting strategy when engine size or vehicle loading changes. The control strategies used in ALPHA are modeled after strategies observed during actual vehicle testing.

Vehicle packages defined within ALPHA can be run over any pre-determined vehicle drive cycle. To determine fuel consumption values used to calculate LD GHG rule CO_2 values, an FTP and HWFET cycle are simulated, separated by a HWFET prep cycle as normally run during certification testing. ALPHA does not include a temperature model, so the FTP is simulated within the model assuming warm component efficiencies for all bags. Additional fuel consumption due to the FTP cold start is calculated in post-processing by applying a fuel consumption penalty to bags 1 and 2, depending on the assumed warmup strategy. Any vehicle drive cycle can be defined and fuel economy simulated in ALPHA. For example, the results from the US06, NEDC, and WLTP cycles (among others) are used to tune vehicle control strategy parameters to match simulation results to measured vehicle test results across a variety of conditions. In addition, performance cycles have been defined, which are used to determine acceleration performance metrics.

2.3.3.3.2 *Detailed ALPHA Model Description*

The ALPHA model architecture is comprised of four systems: Ambient, Driver, Powertrain, and Vehicle as seen in Figure 2.93. With the exception of Ambient and Driver, each system consists of one or more subcomponents. The function of each system and its respective

[CCC] The GEM model has also been peer reviewed multiple times, and was the subject of intense comment during the rulemaking adopting the second phase of GHG standards for heavy duty vehicles and engines. See 81 FR 73530-531, 538-549.

component models are discussed in this chapter. The structure and operation described in this section incorporate numerous constructive comments from both public comments and peer reviews. The model has been upgraded to integrate new technologies, improve the fidelity of the simulation results and better match the operation of the benchmarked vehicles. This all supports our primary goal of accurately reflecting changes in technology for both the current and future light duty fleet. As part of this effort, substantial effort has been put forth to accurately track and audit power flows through the model to ensure conservation of energy, and provide better data on technology effectiveness.

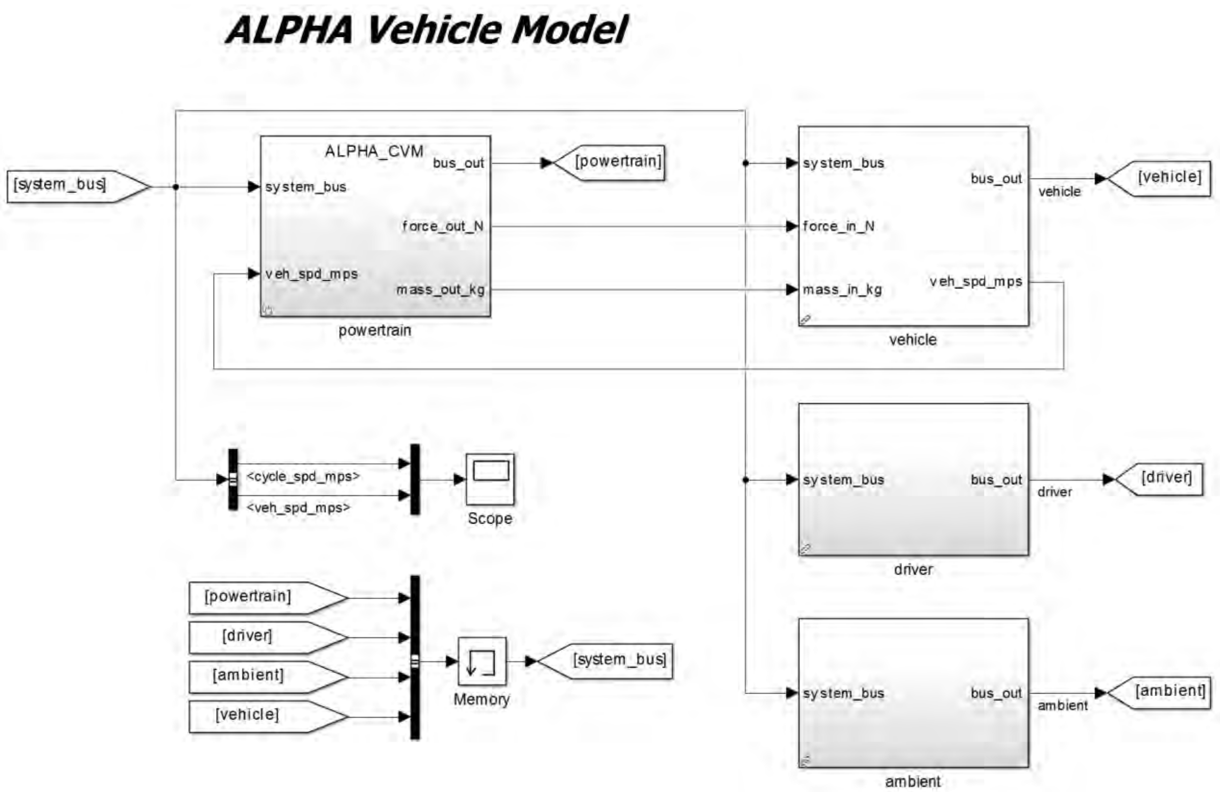


Figure 2.93 ALPHA Model Top Level View

One unique feature of ALPHA is the use of dynamic lookup tables. These special lookup tables provide interpolation similar to a normal Simulink 1D or 2D lookup, but allow the dimensionality and signals used for lookup to be determined at run time. This allows tables in the model such as transmission losses to be parameterized in a way that best matches the available data for that particular component. For example, a detailed transmission map may have had its losses characterized by gear number, input speed, input torque, hydraulic line pressure and temperature using a five dimensional lookup, while other testing might yield much simpler two dimensional map utilizing only input torque and speed. ALPHA can accept either map without physically altering the Simulink structure. Dynamic lookup tables are a powerful tool for improving model fidelity when highly detailed data is available, but also allow the model to run with coarse or simplified data when needed.

2.3.3.3.2.1 Ambient System

This system defines ambient conditions such as pressure, temperature, and road gradient, where vehicle operations are simulated. ALPHA has been calibrated to generate fuel economy results corresponding to chassis dynamometer certification tests; therefore, conditions within the simulation have been maintained to align with current test procedures.

2.3.3.3.2.2 Driver System

The driver model in ALPHA is a purely proportional-integral control driver that features a small look ahead to anticipate upcoming accelerations in the drive cycle. This is especially useful at launch where the vehicle response may be delayed due to the large effective inertia in lower gears. The driver in ALPHA is designed to follow a vehicle speed versus time driving cycle such as the UDDS or HWFET. The driver is tuned to emulate the activities of a real driver during a chassis test, including starting the engine, putting the transmission into gear and then operating both the accelerator and brake pedals.

2.3.3.3.2.3 Powertrain System

The engine, transmission, electrical systems and accessories discussed in the following section are combined to form vehicle powertrain systems. The conventional powertrain system shown in Figure 2.94 contains sub-models representing each of the components. Additional powertrains were constructed to simulate power split and P2 hybrid as well as full electric drivetrains.

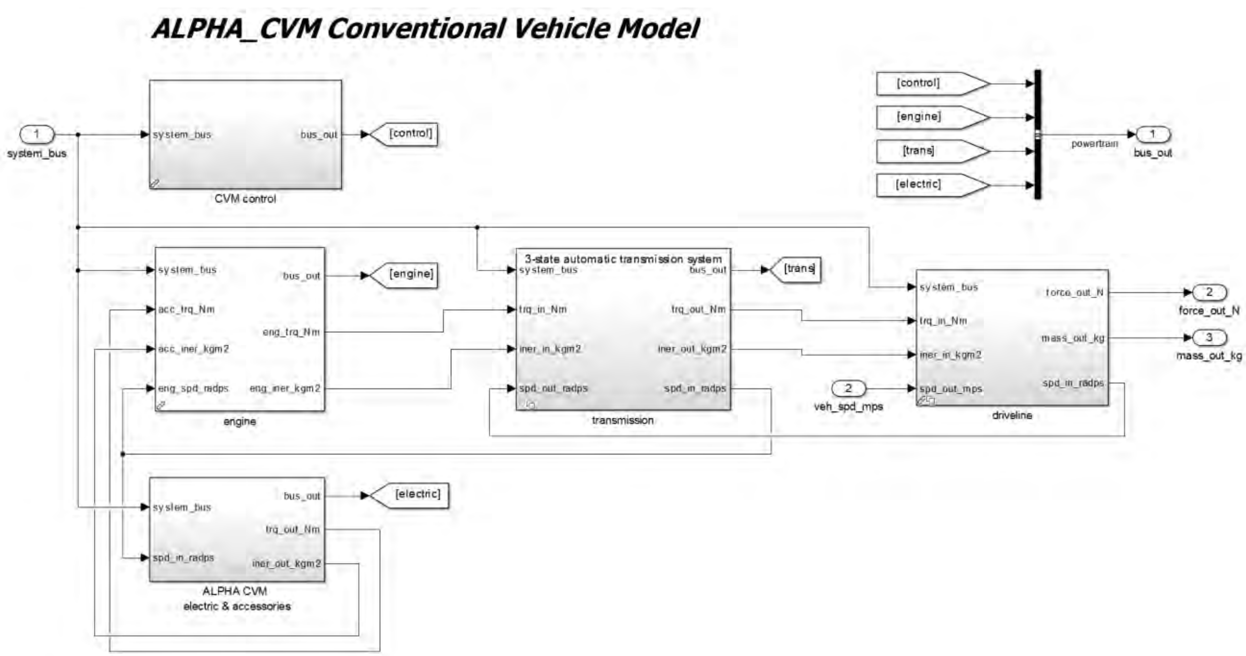


Figure 2.94 ALPHA Conventional Vehicle Powertrain Components

2.3.3.3.2.3.1 Engine Subsystem

The engine model is built around a steady-state fuel map covering all engine speed and torque conditions with torque curves restricting operation between wide open throttle (full load) and closed throttle (no load). The engine fuel maps for various engines are provided by benchmark data, generated via tools like GT-POWER, or adapted from other data sources. The engine fuel map contains fuel mass flow rates versus engine crankshaft speed and brake torque. In-cylinder combustion processes are not modelled.

The steady-state fuel map used in ALPHA is adapted from the available test data or model output by creating an interpolant grid covering the area between idle speed and redline speed, and between the wide open throttle and closed throttle curves. In some circumstances, portions of the map (for example, those near redline speed or near the closed throttle curve) are extrapolated from the original data. In general, these areas represent engine operation which is either outside of that used in two-cycle operation (near redline speed) or which uses little fuel in general (near the closed throttle curve).

During the simulation, the engine speed at a given point in the drive cycle is calculated from the physics of the downstream speeds. The quantity of torque required is calculated from the driver model accelerator demand, an idle speed controller, and requests from the transmission during shifts. The torque request is then limited by a torque response model which has been tuned to match the torque response of naturally aspirated and turbocharged gasoline and diesel engines. The resulting engine torque and speed are used to interpolate a fuel rate from the fuel map.

Additional sources of fuel consumption documented in benchmarking activities have been included in the model as well. On gasoline engines, the torque management that occurs during shifting is implemented such that the reduction in torque does not cause a corresponding reduction in the fuel rate. This approximates the effect of the observed spark retard to lessen the lurch associated with decelerating engine inertia during upshifts. Another source of additional fueling occurs after engines transition out of decel fuel cutoff. Additional fuel is applied for a few seconds for emissions control. Finally, there are additional fuel penalties applied within the simulation associated with rapid changes in engine power.

2.3.3.3.2.3.2 Electric Subsystem

The electric subsystem consists of 3 major components: battery, starter, and alternator.

The battery model for ALPHA was created after a literature review of battery models, particularly for hybrid vehicle applications. The same battery model structure[544,545] is used for both conventional and hybrid vehicles, with different calibrations used to simulate different chemistries such as lead-acid or lithium ion. The model features an open circuit voltage that varies with state of charge, a series resistance, and dual RC time constant filters to provide realistic voltage response. Calibrations were generated from published literature or EPA benchmark testing for the open circuit voltage and transient behavior. The simulated battery also features a thermal model, with the output current limited at extremes in temperature or state of charge.

The engine starter is modeled as a simplified electric motor. It has a fixed efficiency and is commanded via a Boolean activation signal. The operation of the starter is characterized by a desired cranking speed and a torque capacity. These values are generally calculated to match the engine specifications. When an engine start is requested a proportional integral controller is used to determine the torque applied to accelerate the engine to the desired cranking speed, limited by the torque capacity. The mechanical power required and efficiency then determine the resulting electrical power consumed.

The engine alternator is modeled as a simplified electric generator with a fixed efficiency. The electrical output current is determined by a charging controller. The efficiency and electrical power output can then be used to compute the mechanical load applied to the engine. The charging controller can operate in two different modes. In a basic mode it always tries to charge the battery to a fixed voltage target. It also features an adaptive charging / alternator regen mode that varies the voltage target and thus current output based on driving conditions. Lower electrical output is provided during cruising, enough to maintain a minimal state of charge. During decelerations and transmission upshifts electrical output and thus mechanical load are increased to capture energy that would otherwise be dissipated via the brakes or transmission. The adaptive charging / alternator regen strategy exhibits increased variability of battery state of charge over various driving cycles. Therefore, it is necessary to precondition the model with a prep cycle just as would be done on a test such as the HWFET to get accurate results.

2.3.3.3.2.3.3 Accessories Subsystem

The accessories subsystem in ALPHA is responsible for applying electrical and mechanical loads to mimic those observed during testing. The system is capable of applying 4 different loads: power steering, air conditioning, fan and a generic load to cover the remaining losses observed. Each load can apply mechanical loads to the engine crankshaft and/or electrical loads to the battery. Each load can be independently correlated to model signals via dynamic lookup tables, and is calibrated to match test data. Baseline vehicles with mechanical power steering often have mechanical losses that vary with engine speed, while future vehicles featuring electric power steering may have electrical losses that vary with vehicle speed.

2.3.3.3.2.3.4 Transmission Subsystem

The transmission subsystem features different variants representing the major types of transmissions (AT, DCT, and CVT) that are currently used in LD vehicles. The different transmission models are built from similar components, but each features a unique control algorithm matching behaviors observed during vehicle benchmarking.

One of the features in ALPHA, which is required for the model to conserve energy, is multiple speed integrators. One is located at each of the points in the driveline where rotational inertias may become decoupled such as the transmission gearbox. These integrators use the torque and upstream inertia to compute the resulting acceleration and thus speed for the upstream components. For couplings that may become locked up, such as a clutch, the torques and rotational inertia are then passed down toward the next integrator in the model. This allows the physics of the system to be accurately simulated, losses associated with clutch slip to be computed, and the energy audit to be properly accounted.

2.3.3.3.2.3.4.1 Transmission Gear Selection

All of the gear transmission models use a dynamic shift algorithm, ALPHAshift,[543] to determine the operating gear over the cycle. This employs a rule based approach utilizing the engine torque curve and fuel map to select gears that optimize efficient engine operation and provide performance reserves as a traditional transmission calibration would. The ALPHAshift algorithm attempts to select the minimum fuel consumption gear after applying constraints on engine speed and torque reserve. It also allows downshifts due to high driver demand.[DDD]

The ALPHAshift algorithm contains calibration parameters that can be tuned to match benchmarked shift behavior data from a particular engine and transmission. A generic calibration tuning strategy has been developed from these specific benchmarked calibrations, and is useful for simulating the shifting behavior of engine and transmission combinations that are from different vehicles or represent future technologies.

The CVT transmission model uses a similar ALPHAshift-CVT[546] algorithm for determining gear ratio selection. It attempts to maintain operation on an engine speed versus requested power line that minimizes fuel consumed. This method also has constraints for minimum engine speed and the rate at which the gear ratio can be changed.

2.3.3.3.2.3.4.2 Launch Clutch Model

The clutch model in ALPHA can be modulated during launch (for manual and automated manual transmissions) and requires a fixed time to engage. Torque is conserved across the clutch during engagement and the inertial effects of accelerating and decelerating the upstream inertias are captured. This additional fidelity necessitates a more complicated control algorithm to manage clutch slip during launch which is included in the control strategy for the appropriate transmissions.

Two clutches are bundled together to create the dual clutch module for the dual clutch transmission. The dual clutch features a single integrator for calculating engine speed during shifts.

2.3.3.3.2.3.4.3 Gearbox Model

The gearbox model for ALPHA has been developed with the goal of simulating realistic operation during shifts for all types of transmissions. The gearbox contains gear ratios and properly scales torque and rotational inertia through the ratio change. Power losses within the gearbox are applied via dynamic lookup tables which determine torque loss and/or gearbox efficiency. These loss tables are typically constructed using signals such as input torque, input speed, commanded gear and/or line pressure.

Realistic shifting behavior is achieved with appropriate delays provided by a synchronizer clutch model. The layout of the gearbox model is most similar to a manual transmission, but the application for a planetary gearbox is a reasonable approximation once the neutral delay between gears is omitted.

The gearbox rotational inertias are split between a common input inertia, common output inertia and a gear specific inertia. The common inertias represent rotational inertia always coupled to the input or output shafts. The gear specific inertias, which are only used for planetary automatic transmissions, are added or removed as gears are engaged or disengaged. There is an additional load placed on the powertrain associated with spinning up each gear specific inertia,

[DDD] Also known as a power downshift or kickdown.

and when each gear is disengaged the kinetic energy contained within the gear specific inertia is discarded and treated as a loss.

2.3.3.3.2.3.4.4 Torque Converter Model

The torque converter model in ALPHA simulates a lockup-type torque converter. The torque multiplication and resulting engine load are calculated via torque ratio and K factor curves that vary as a function of speed ratio across the torque converter. Base torque ratio and the K factor curves are often scaled in situations where detailed torque converter information is unavailable.

The lockup behavior of the torque converter is accomplished by integrating a clutch model similar to the one discussed above. The torque converter model also contains a pump loss torque that is implemented via a dynamic lookup table to simulate the power required to operate the pump on an automatic transmission or CVT. When possible, pump losses are measured separately during the component benchmarking process, and are generally represented as a function of torque converter input speed and transmission line pressure.

2.3.3.3.2.3.4.5 Automatic Transmission & Controls

The automatic transmission (AT) is composed of the torque converter and gearbox systems discussed above. The AT is allowed to shift under load. During upshifts and torque converter lockup the engine output torque is slightly reduced to minimize the resultant torque pulse encountered by decelerating the engine inertia.

The torque converter lockup clutch command is determined based on transmission gear and gearbox input speed. The thresholds that trigger lock and unlock of the torque converter are calibrated to match benchmark data.

2.3.3.3.2.3.4.6 DCT Transmission & Control

The ALPHA DCT model is constructed from two separate gearbox components and a dual clutch module as described above. The dual clutch module features a dynamic lookup torque loss table that can be used to represent all the gearbox losses in one location if loss information for the separate gearboxes is not available. After a gear change to a new preselected gear is requested, the dual clutch module will transition and begin applying torque through the new gear.

The DCT transmission controller also includes a low speed clutch engagement routine to feather the clutch for low speed operation or launch. Similar to the automatic transmission, engine output torque is reduced during upshifts to minimize the torque pulse at the wheels and to prevent excessive clutch slip.

2.3.3.3.2.3.4.7 CVT Transmission & Control

The CVT transmission in ALPHA consists of the torque converter and gearbox modules. When operating as a CVT the gearbox maintains a state of partial engagement allowing the gear ratio to be constantly changed.

2.3.3.3.2.3.4.8 Driveline

The driveline system contains all of the components that convert the torque at the transmission output to force at the wheels. This includes drive shafts as well as driven axles, consisting of a differential, brakes and tires. ALPHA is capable of simulating multiple axles, but it is often simpler to convert a driveline to a single axle equivalent.

The driveshaft is a simple component for transferring torque while adding additional rotational inertia. It is only used for rear wheel drive vehicles.

The final drive is modeled as a gear ratio change with an associated torque loss and/or efficiency. These losses are applied via a dynamic lookup table. For front wheel drive transmissions, the final drive losses are often difficult to separate. In these situations, all losses are applied in the gearbox.

The brake system on each axle applies a torque to the axle proportional to the brake pedal position from the driver model. The brake torque capacity is scaled to match the stopping requirements of the vehicle.

The tire component model transfers the torques and rotational inertias from upstream components to a force and equivalent mass that is passed to the vehicle model. This conversion uses the loaded tire radius and adds the tire's rotational inertia. A force associated with the tire rolling resistance is not simulated because these losses are included in the road load ABC coefficients applied within the vehicle subsystem (when using ABC coefficients, ALPHA is also capable of using separate rolling resistance and aerodynamic drag coefficients).

2.3.3.3.2.3.5 Vehicle System

The vehicle system consists of the chassis, its mass and forces associated with aerodynamic drag, and changes in road grade. The vehicle system also contains the vehicle speed integrator that computes acceleration from the input force and equivalent mass which is integrated to generate vehicle speed and distance traveled. The road load force is calculated from the ABC coefficients based on coast down testing, or aerodynamic drag coefficient and frontal area data.

2.3.3.3.3 Energy Auditing

One of the quality control components within the ALPHA model is an auditing of all the energy flows. This auditing enables verification that the physics represented in the model is done correctly, generally resulting in a simulation energy error less than a few hundredths of a percent. The audit data can also be compared between simulations to verify that individual component losses are reasonable when compared to baseline packages or products that may feature similar technologies. An example energy audit report for a package similar to a current production sedan is shown in Figure 2.95. It should be noted that the lack of final drive losses in this case is attributed to the vehicle being front wheel drive, and the thus the final drive losses are included in the gearbox.

It is important to note that the layout of the Simulink blocks and the mathematical configuration of the model are distinct. For example, the torque out of the engine Simulink block may or may not represent net shaft torque – if downstream loads such as the torque converter or launch clutch are unlocked or decoupled then the net shaft torque, including inertia effects, is determined at the integrator which is located in the Simulink block representing the decoupled device. For this reason, the auditing of the energy flows within the model is accomplished by carefully observing the physics of the model as opposed to simply data logging the Simulink block input and output ports.

```
        ---- Energy Audit Report ----
Total Energy Consumed               = 205975.66 kJ
    Fuel Energy                     = 205971.83 kJ
    Stored Energy                   =      3.83 kJ
         Battery Internal Losses =      0.91 kJ      0.00%
    Kinetic Energy                  =      0.00 kJ
    Potential Energy                =      0.00 kJ

Usable System Energy Provided       = 63307.72 kJ
    Engine Energy                   = 63304.80 kJ
         Engine Efficiency          =    30.73 %
    Stored Energy                   =     2.92 kJ
    Kinetic Energy                  =     0.00 kJ
    Potential Energy                =     0.00 kJ

Energy Consumed by ABC roadload     = 37465.54 kJ     59.17%
Energy Consumed by gradient         =     0.00 kJ      0.00%
Energy Consumed by brakes           = 11429.43 kJ     18.05%
Energy Consumed by Accessories      =  3505.29 kJ      5.54%
    Starter                         =     0.45 kJ      0.00%
    Alternator                      =  1225.99 kJ      1.94%
    Battery Stored Charge           =     0.00 kJ      0.00%
    Engine Fan                      =     0.00 kJ      0.00%
         Electrical                 =     0.00 kJ      0.00%
         Mechanical                 =     0.00 kJ      0.00%
    Power Steering                  =     0.00 kJ      0.00%
         Electrical                 =     0.00 kJ      0.00%
         Mechanical                 =     0.00 kJ      0.00%
    Air Conditioning                =     0.00 kJ      0.00%
         Electrical                 =     0.00 kJ      0.00%
         Mechanical                 =     0.00 kJ      0.00%
    Generic Loss                    =  2278.85 kJ      3.60%
         Electrical                 =  2278.85 kJ      3.60%
         Mechanical                 =     0.00 kJ      0.00%
    Total Electrical Accessories =  2278.85 kJ      3.60%
    Total Mechanical Accessories =     0.00 kJ      0.00%
Energy Consumed by Driveline        = 10913.96 kJ     17.24%
     Launch Device                  =  1796.61 kJ      2.84%
     Gearbox                        =  8150.72 kJ     12.87%
         Pump Loss                  =  3243.10 kJ      5.12%
         Spin Loss                  =  2837.18 kJ      4.48%
         Gear/Inertia Loss          =  2070.44 kJ      3.27%
     Final Drive                    =     0.00 kJ      0.00%
     Tire Slip                      =   966.63 kJ      1.53%
Net System Kinetic Energy Change =     0.44 kJ      0.00%
                                      ------------
Total Loss Energy                   = 63314.66 kJ
Simulation Error                    =    -6.94 kJ
Energy Conservation                 =  100.011 %
```

Figure 2.95 Sample ALPHA Energy Audit Report

2.3.3.3.4 ALPHA Simulation Runs

ALPHA was used to perform a series of simulation runs, where various technology packages were compared to exemplar vehicles. The exemplar vehicles have been adjusted from those used in the FRM and Draft TAR to better represent the MY2015 vehicle baseline used in the OMEGA analysis for this Proposed Determination as described in Section 2.3.3.2.2. Four acceleration performance metrics were calculated for the exemplar vehicles: 0-60 time, ¼ mile time, 30-50 passing time, and 50-70 passing time. These metrics were chosen to give a reasonably broad set of acceleration metrics that would be sensitive enough to represent true acceleration performance, but not so sensitive that minor changes in vehicle parameters would significantly change the final metric.

For each subsequent comparative run, a vehicle package was defined within ALPHA by specifying powertrain components and road load specifications. ALPHA's road load force at a specific vehicle velocity (v) is determined by using the following formula: $F = Cv^2 + Bv + A$

where the coast down coefficients (A, B, and C) are derived from a least squares fit of data from track coast-down tests.

In ALPHA modeling, it is assumed that the A coefficient is a factor for the road load force that is mostly associated with tire rolling resistance, the B coefficient is a small factor, which represents higher order rolling resistance and gearing loss factors, and the C coefficient is a factor which mostly represents aerodynamic drag. Thus, changes in aerodynamic losses are modeled by changing the C coefficient, and changes in rolling resistance losses are modeled by changing the A coefficient. Changes in mass reduction are modeled by reducing the test weight, and by reducing the A coefficient (as rolling resistance is a function of vehicle weight).

For each of the six vehicle class described in Section 2.3.1.4, an exemplar configuration was chosen and was run over the performance cycle, and the times for each performance metric were extracted. These four metrics were summed for the exemplar vehicle. For each vehicle technology package based on the same vehicle class, a nominal engine size was determined based on the estimated performance effect of the technologies included in the package and a set of packages with a range of engine sizes larger and smaller than the nominal engine size were simulated. The same performance cycle was run and the sum of the four metrics compared to the exemplar sum for each engine size package. Results where the sum was not equal to or less than the exemplar sum (more stringent than the 5 percent band suggested by NAS) were rejected. The drive cycle CO_2 emissions of the target package were taken from the lowest emissions result of the remaining results.

To account for changes in engine efficiency as a result of resizing for simulation, a set of adjustments was developed. First, based on the overall size the architecture of the engine (I3, I4, V6, and V8) is selected so that the scale factor for cylinder volume could be calculated. The first adjustment is related to the changes in heat transfer that result from altering the surface to volume ratio of the cylinder. Increasing cylinder volume leads to a lower percentage of combustion energy transferred to the engine head and block resulting in higher efficiency. The adjustment factor was derived from published test data[547] and is supported by other literature.[548] The second adjustment modifies engine friction. Literature contains methodologies for estimating engine FMEP based on various engine dimensions.[549,550] Using inputs consistent with current production engines estimates of FMEP for various architectures and displacements were generated. Using the FMEP estimates for the original and resized engines an adjustment can be applied to the fuel map and other parameters related to engine torque. The third adjustment relates to the increased knock sensitivity of engines when increasing cylinder volume. As engine bore increases the higher knock tendency drives more retarded spark timing and thus lower efficiency. The knock sensitivity is characterized using trends in the original fuel map, and from this an adjustment can be made that reduces efficiency during low speed high load operation. The net result of these adjustments when scaling an engine of fixed architecture up to a larger displacement are efficiency reductions at low speed and high load and increases over the remainder of the map.

2.3.3.3.5 *Post-processing*

ALPHA simulation runs are performed assuming warm component efficiencies. Additional fuel consumption due to the FTP cold start is calculated in post-processing by applying a fuel consumption penalty to bags 1 and 2. These fuel consumption penalty factors represent additional fuel used to heat the catalyst, and additional energy lost to higher viscosity lubricating oil in the engine and transmission. The fuel consumption penalties for "present" and "past" vehicles (component vintaging is discussed in 2.3.3.3.6) are set at 15 percent (present) to 17 percent (past) for bag 1 and 2.5 percent for bag 2. The penalty factors are applied during post-processing so that the fuel consumption for the appropriate bag is increased by the indicated amount. These factors were determined by comparing the "cold" FTP bags 1 and 2 to the "warm" bags 3 and 4 for a range of vehicles.

Since the three-bag FTP is a standard test, the difference in fuel consumption between bags 1 and 3 of the FTP could be calculated for the entire fleet (available in the Test Car List data files[551]), as seen in the graph below. However, the data sources for bag 4 are more limited. EPA based the 2.5 percent penalty factor on test data available from conventional vehicle testing from Argonne National Labs[552] and from internal testing, where differences between bags 2 and 4 averaged about 2.5 percent.

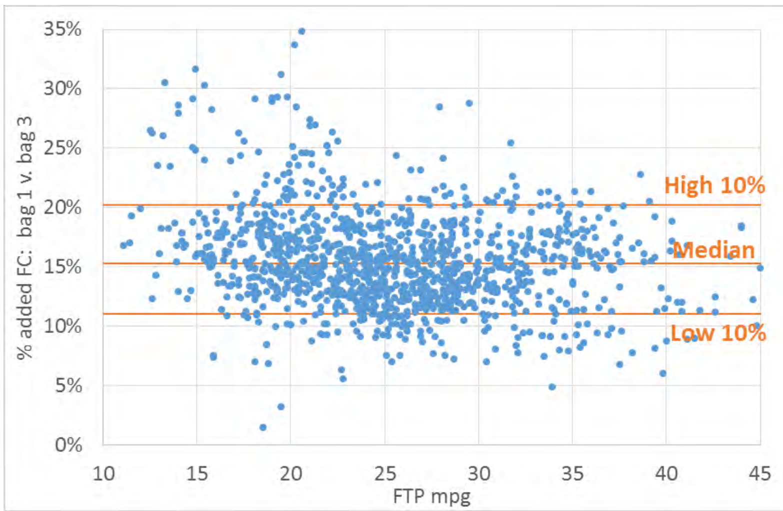


Figure 2.96 Example: Difference in 2016, Between Bags 1 and 3 of the FTP, from the Test Car List.

For simulation of advanced vehicle packages which included thermal management of the engine or transmission, the penalty factors were reduced (to a minimum of 11 percent for bag 1 and 0 percent for bag 2) to account for the reduction in losses associated with faster component warmup.

2.3.3.3.6 Vehicle Component Vintage

Vehicle components (engines, transmissions and accessory loads) are assigned a vintage of "past," "present," or "future." The vintage of the component determines the assumed technology package associated with the component, and thus the default value of some associated parameters.

One parameter affected by vintage is electric accessory loading. The "past" value for electrical loads includes a base electrical load of 154 W, additional power draw based on engine speed (approximately 700 W at 2500 rpm and 1050 W at 6000 rpm), and an alternator efficiency of 55 percent. These values assume mechanical power steering. The "present" value for electrical load includes a base electrical load of 390 W, no additional variable accessory power draw, and an alternator efficiency of 65 percent. This is based on loads measured in various tested vehicles, SAE technical papers and stakeholder feedback. The "future" electrical load assumes a 290 W base electrical load, but with a high-efficiency (70 percent efficient) alternator that also employs an alternator regen strategy.

Future vintage transmissions are also assumed to be associated with reduced parasitic losses and early torque converter lockup.

Although the assigned vintage determines default values for accessory loads and cold start penalty, these defaults can be overridden in the model to examine the effects of specific technologies separately.

2.3.3.3.7 Additional Verification

As an additional verification of ALPHA model simulations, EPA compiles and executes technology package combinations using a hardware-in-the-loop (HIL) system. This process enables powertrain, vehicle, and driver behavior to be observed in real time for both on-cycle and off-cycle situations. Any undesirable behavior is analyzed and used to fine tune the modeling process. These compiled HIL models are also utilized by EPA as part of the vehicle benchmarking process when testing vehicle subsystems such as engines, transmissions, battery modules, and other components. Figure 2.97 shows an example ALPHA model simulation observation display.

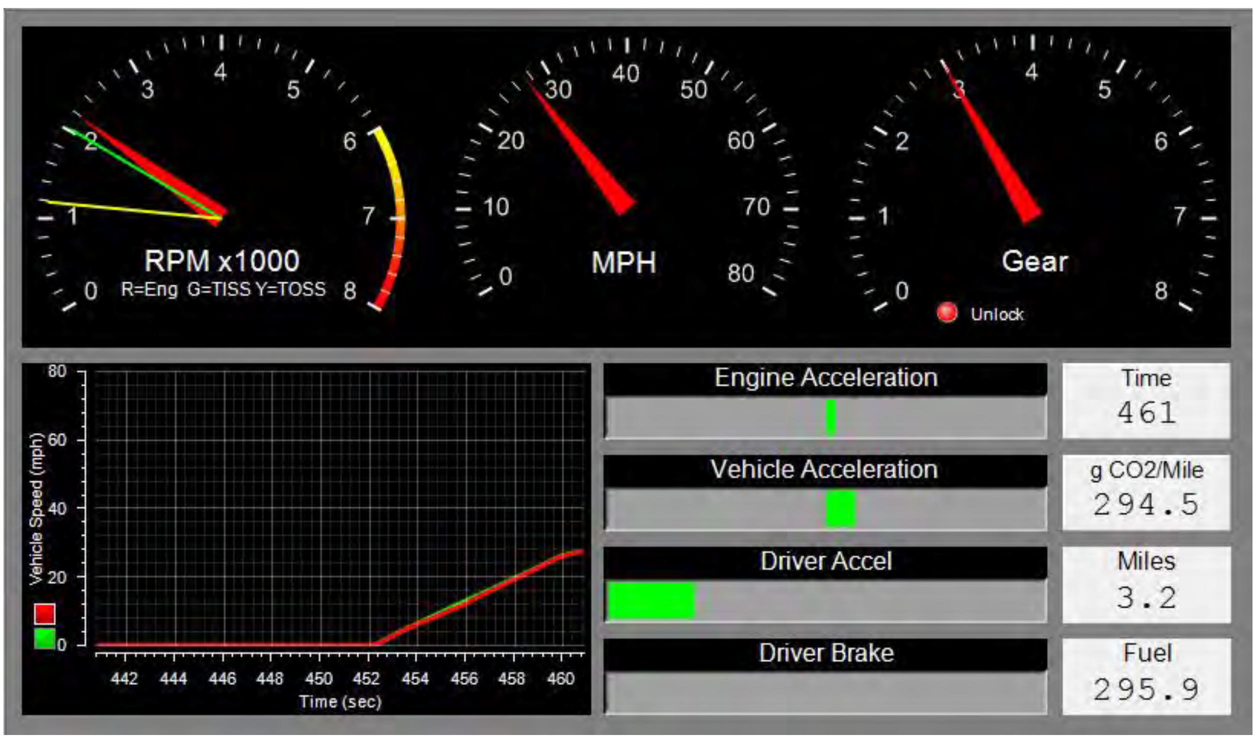


Figure 2.97 Example ALPHA Model UDDS Simulation Observation Display

As part of EPA's on-going quality process, comparative analyses were completed by EPA as part of the ongoing MTE work. When viewing full vehicle simulation models as a calculator, providing the same inputs to the calculators should provide the same outputs. The first set of comparisons used Ricardo EASY5 inputs from the MY2017-2025 Light-Duty FRM as inputs to the ALPHA model. The EASY5 and ALPHA results showed only minor differences. The second set of comparisons used a set of inputs provided by the Autonomie model. Again the Autonomie and Alpha models showed only minor differences between simulation results due to specific model behaviors or implementations, convincing EPA that these models are very close in terms of computational results when run using the same input data and assumptions.

2.3.3.3.8 Key Public Comments Related to the ALPHA Model

Because the ALPHA model reaches into many facets of EPA's technology assessments, many of the topics touched upon in comments on the Draft TAR can be seen as related in some way to the ALPHA model. This section gathers some of the key comments that either directly concern the design or use of the ALPHA model or were conveyed in the context of a discussion of the ALPHA model. Some comments cited here are better addressed in the context of a more specific topic, and in those cases the reader is directed to the TSD chapter where the comment is addressed.

Some comments recognized the importance of EPA's use of ALPHA, a physics-based, forward-looking simulation tool that is available to the public. The International Council on Clean Transportation (ICCT) noted, "EPA's new physics-based ALPHA model offers a nice enhancement in modeling multiple technologies." The Union of Concerned Scientists (UCS) also noted, "EPA extensively employed its own, freely accessible ALPHA full-vehicle modeling tool, which was extensively peer-reviewed and benchmarked against its work at its laboratory, which also resulted in numerous peer-reviewed publications. This laboratory analysis allowed for combinations of technologies not available on the road today to be analyzed, including both combinations of turbocharged engines with advanced transmissions and future high-compression ratio engines."

The Alliance of Automotive Manufacturers, Global Automakers, and other stakeholders provided detailed comments regarding the ALPHA Model.

A comment from the Alliance suggested that EPA use the Autonomie model in place of the ALPHA model, on the grounds that the industry is more familiar with Autonomie. In response, the ALPHA model was developed to eliminate the "black box" and copyright issues with commercial modeling products to allow full transparency in the modeling process. The ALPHA model is designed to function in a compliance environment and to be publicly available without any hidden or proprietary aspects.

While not directly related to the ALPHA model (but rather its inputs), one commenter stated, "The engine maps used by the full vehicle simulation models do not fully consider key technical issues, and are therefore generally optimistic." Comments on engine maps and similar inputs used in the Draft TAR analysis are considered and discussed in Chapter 2.3.4.1 (Engines: Data and Assumptions for this Assessment) of this TSD.

The Alliance commented, "There are a number of technical flaws that are common to both the ALPHA and Autonomie models which bias the full vehicle simulations to more optimistic benefits than those anticipated by automakers." The comment continued by suggesting that this was related to several aspects of criteria emissions compliance that the Alliance felt could impact CO_2 and fuel economy performance as projected in the analysis, stating: "The Alliance recommends that both Agencies account for the CO_2 and FE degradation associated with Tier 3 emissions control systems and the impact of more stringent evaporative emissions regulations in their MTE analysis. The effect of the evaporative emissions regulations is further magnified for engine stop-start and HEV applications where the engine off option is constrained by the need to purge the canister for evaporative emissions requirements." In a related comment, the Alliance recommended "that both Agencies account for and include the detrimental impact of CARB particulate matter (PM) (1 mg/mi) regulations on CO_2 and FE performance in the MY2022–2025 time frame. The 1 mg/mi PM (1) requirement could impact approximately 40 percent of the fleet."

Regarding criteria pollutant emissions, EPA developed the Tier 3 program in full consideration of both the light duty and heavy duty GHG programs that would be occurring in the same time frame as the phase-in of the Tier 3 rule. In fact, many of the program's key dates including the final MY2025 standards were specifically coordinated to allow the criteria pollutant and GHG programs to work together in a complementary fashion and leverage technology synergies. As an example, downsized engines used to comply with the GHG requirements of lower CO_2 emissions generally also produce lower engine out criteria pollutant emissions. Lower engine out criteria emissions facilitate manufacturer's task of reducing the final tailpipe emission levels required to meet Tier 3 standards. Another technology used to reduce criteria pollutant emissions involves reducing or minimizing the amount of fuel enrichment used for cold starts. This reduction in fuel used for starting and running a cold engine translates directly to lower fuel consumption and therefore reduced CO_2 emissions during the cold start and warm-up. EPA recognizes that certain strategies used today to reduce criteria pollutant emissions, particularly elevated idle speeds and retarded timing used initially following a cold start to warm-up the catalyst, can temporarily reduce engine efficiency. However, manufacturers have other options that result in similar benefits for criteria pollutant emissions without a CO_2 or fuel economy penalty. This includes other methods to more rapidly warm the catalyst such as insulated exhaust pipes or better catalyst design and placement. Additional discussion of the comment regarding CO_2 emissions may be found in Chapter 2.3.1.3 (Fuels) of this TSD.

Regarding evaporative emission challenges, Tier 3 standards did not result in an increase in the amount of purge required to meet evaporative emission requirements from what was already required in the Tier 2 program. Instead, it requires improvements to evaporative hardware to prevent or capture any residual fuel related emissions. EPA recognizes that technologies that reduce engine operation such as stop-start and HEV applications also result in reduced opportunity to purge the evaporative canister of fuel vapors. Manufacturers have successfully designed and produced evaporative emission control system technologies to deal with the challenge of reduced purge opportunity. These technologies include sealed or partially sealed fuel systems that produce less fuel vapors that would need to be purged by running the engine. Additionally, EPA has historically worked with manufacturers to adjust test procedures when a new technology is not appropriately evaluated over existing test procedures and protocols.

Regarding Federal PM emissions standards, many vehicles, including those with naturally aspirated and turbocharged/downsized GDI engines, already have PM emissions sufficiently low to comply with Tier 3 PM emissions standards with a compliance margin. Vehicles with PFI-equipped engines typically have PM emissions over the FTP that are 25 percent to 50 percent of the proposed future California LEV III 1 mg/mi PM standard over the FTP chassis dynamometer test. EPA certification and confirmatory emissions data on vehicles equipped with dual-injection systems (both PFI and GDI) such as vehicles equipped with Toyota's 2GR-FSE and 4U-GSE engines have PM emissions over the FTP drive cycle that are comparable to PFI engines and thus well below 1 mg/mi PM over the FTP. Toyota is applying dual injection to other engines, such as the 8AR-FTS 2.0L turbocharged Miller Cycle engine to improve efficiency and drivability. Ford recently announced application of a similar dual-injection strategy to model year 2017 and later light-duty trucks equipped with the 3.5L EcoBoost engine. Dual-injection represents one approach to achieve sub-1 mg/mi PM emissions over the FTP drive cycle with potential for reduced CO_2 emissions, low PM emissions, and improvements in catalyst light-off performance for improved NO_x and NMOG emissions. The best GDI and turbocharged GDI engines (without dual-injection) currently have PM emissions of between 1.0 and 3.0 mg/mi. At the 2015 EPA Ultrafine Particle Workshop, AVL presented a range of strategies to bring GDI engines into compliance with future California LEV III PM standards, and also future EU Euro 6 SPN standards.[553] AVL found via in-cylinder optical measurements that conditions with high flame luminance could be used to indicate the presence of non-homogeneous, diffusion-limited combustion associated with soot pyrolysis and particle formation. Methods identified by AVL to reduce diffusion-limited combustion in GDI engine applications included:

- Reducing fuel impingement onto surfaces via changes in injector spray targeting, piston bowl shape, injection event timing and use of multiple injections per combustion cycle.
- Changes to spark timing and injection events to directly heat the piston following cold startup to improve the vaporization of impinged fuel.
- Changes to the catalyst heat-up strategy used to improve catalyst light-off after cold start, including further optimization of the timing and duration of multiple injection events.

Eight recent engine development programs conducted by AVL that began with SPN emissions at up to 6 times the EU6c standards were successfully reduced to 15 percent to 45 percent of the EU6c PN standards using such combustion refinements. While not a direct indication of PM emissions, vehicles capable of emissions at less than half the EU6c SPN standard would likely have PM emissions well under the future California LEV III 1 mg/mi standard.

In summary, the best currently available GDI technology has already achieved criteria pollutant emissions consistent with future Federal Tier 3 PM emissions standards. One fueling strategy for use with GDI engines, dual-injection, has demonstrated the capability of meeting the future proposed LEV III PM emissions standard of 1 mg/mi over the FTP beginning in 2025 if such a standard is approved for implementation by the California Air Resources Board. Further combustion system refinements using more conventional GDI systems (i.e., a single injection system) appear to have the capability of meeting the proposed 1.0 mg/mi FTP standard when taking into account the lead time available prior to implementation of these standards and assuming that a 1.0 mg/mi FTP PM standard is finalized in California.

With regard to electrical accessory loads, the Alliance suggested that "the Agencies harmonize around the NHTSA base electrical accessory loads of 240 W", further commenting, "the base electrical loads used by the Agencies differ by a factor of two. While there are some vehicles that do reach 490W and greater, the average two-cycle base load of the sample vehicles is 387W. By inflating the base electric load, EPA has effectively overestimated the effectiveness of load reduction technologies. "In response, the “Table A-2: Electrical Base Load Benchmarking Data” provided by the Alliance is appreciated, and agrees well with the “present vintage” vehicle accessory load of 390 W used in ALPHA for the Proposed Determination. For more details on EPA's assumptions for accessory loads, please refer to "2.3.3.3.6 Vehicle Component Vintage" of this TSD.

The Alliance also recommended "that NHTSA and EPA harmonize and use regular grade Tier 3 test fuel for all future analysis, unless testing 'premium required' engines … In addition, Tier 3 test fuel also contains 10 percent ethanol, lowering the energy content of the fuel." Consideration of this comment is found in Chapter 2.3.1.3 (Fuels) of this TSD.

Another comment stated, "When adjusting engine size to maintain performance, EPA assumes that any resulting engine displacement will be available, maximizing the modeled benefits of various technologies. In practice, manufacturers have a limited number of engine displacements to choose from and will likely select the size of engine that maintains or improves performance. EPA's assumption of infinite engine displacement availability yields unreasonably optimistic results." EPA notes that engine resizing for performance neutrality is a modeling convenience that allows an overall fleet-wide estimation of CO_2 reduction while accounting for the effects of performance, as recommended by the NAS. EPA does not expect manufacturers to rigidly maintain performance, footprint, or any other characteristics of a specific vehicle for the duration of the rule. Rather, EPA anticipates that manufacturers will use the flexibility of the rule to balance a range of requirements, including the manufacturer's estimation of the availability of engine displacements, when designing vehicles. For a more detailed discussion of the "engine sizing for performance neutrality" topic, please refer to Chapter 2.3.1.2 (Performance Assumptions) of this TSD.

With regard to downsized and turbocharged engines, another comment stated, "displacement to vehicle mass ratio (D/M) provides a simple means to assess whether the degree of downsizing will find market acceptance. By failing to consider this parameter, the Agencies could model engines which will not gain customer acceptance. We recommend that both Agencies … add a constraint which considers the displacement to mass ratio." However, the market has already accepted vehicles with the degree of downsizing reflected within the Draft TAR and the Proposed Determination, which includes segment-leading truck applications like the Ford F150.

With regard to performance neutrality, another comment stated, "A key metric needed to maintain performance neutrality is top gear grade-ability. In contrast, the main metric by which performance neutrality is measured by the Agencies is 0-60 acceleration time … none of the metrics evaluated is a substitute for top gear grade-ability." This comment is considered and addressed in Chapter 2.3.4.2.2 (Effectiveness Values for TRX11 and TRX21) of this TSD.

The Alliance also recommended that "the Agencies incorporate and make readily available quality control parameters that can be used to verify the validity of model results in all output files." EPA notes that the version of ALPHA used for the Proposed Determination generates .csv output files that contain over 150 columns of data and quality control parameters. In addition, since EPA is providing a functional copy of ALPHA on its website, the Alliance can add additional quality control data as desired. TSD Chapter 2.3.3.3.3 (Energy Auditing) also contains a description of the energy flow auditing that describes another useful quality control component in ALPHA.

2.3.3.4 Determining Technology Effectiveness for MY2022-2025

EPA collected information on the effectiveness of current CO_2 emission reducing technologies from a wide range of sources. The primary sources of information were the 2017-2025 FRM, the Draft TAR, public comments on the Draft TAR, EPA's ALPHA model, EPA's vehicle benchmarking studies, the 2015 NAS Report, OEM and Supplier meetings, and industry literature. In addition, EPA considered confidential data submitted by vehicle manufacturers, along with confidential information shared by automotive industry component suppliers in meetings with EPA staff. These confidential data sources were used primarily as a validation of the estimates since EPA prefers to rely on public data rather than confidential data wherever possible.

In the Novation Analytics study commissioned by the Alliance, the analysis assumes that no innovation will occur during MY2022-2025. EPA disagrees and recognizes that technologies will be further developed and introduced for MY2022-2025 and that innovation by automobile manufacturers and suppliers will continue to occur. While it is impossible for EPA to predict all of the technologies that will come to fruition, likely trends can be identified in the development of automotive systems that impact GHG emissions over the next decade. EPA uses methods similar to those used by industry to identify and evaluate emerging automotive technology trends. The use of computer aided engineering (CAE) tools for technology evaluation has been a key source of technology effectiveness data for MY2022-2025 vehicle technology packages. A number of other sources of data are also used to either validate CAE results or as independent sources of effectiveness data. In addition to our review of public comments on the Draft TAR, other sources of data include:

- Engineering analysis of logical developments based on current or near-term technology
- Review of peer-reviewed journal papers, U.S. Department of Energy Reports, and other public sources of peer-reviewed data
- Purchase and review of proprietary reports by major automotive industry analytical firms (e.g., R.L. Polk, IHS Automotive)
- Meetings with automobile manufacturers
- Meetings with Tier 1 automotive suppliers
- Contracts with major automotive engineering design, analysis, and services firms (e.g., FEV, Munro and Associates, Southwest Research Institute, Ricardo PLC) to purchase data or engineering services
- “Proof of concept” research either conducted directly by EPA at EPA-NVFEL or under contract with engineering services firms
- CAE tools, including:
  - Engine modeling (e.g., Ricardo WAVE, Gamma Technologies GT-POWER)
  - Vehicle modeling (e.g., EPA LPM, EPA ALPHA, Ricardo RSM, MSC EASY5)
  - HIL simulation of drive cycles
  - Computational fluid dynamics (CFD) for initial component development
- Chassis dynamometer testing
- Engine dynamometer testing
- Transmission dynamometer testing

Data from all sources listed above is used to develop and validate vehicle effectiveness within the EPA ALPHA model and EPA LPM. Modeling of technology package effectiveness within the ALPHA model and LPM is the source of all technology package effectiveness data contained within the OMEGA cost-effectiveness analyses. With respect to engine and powertrain technologies, the general progression of data into the OMEGA analyses has been:

- Develop physics-based models of the technology with extensive validation of a base configuration to actual hardware (e.g., validation of an engine model to actual engine performance, combustion measurements and knock characteristics)
- Use the validated physics-based model to evaluate hardware changes and to develop calibrations necessary to account for such hardware changes
- Use the ALPHA model to determine the CO_2 effectiveness of the powertrain package for different vehicle configurations
- Compare the energy balance of ALPHA model results with vehicle benchmark results as an additional plausibility analysis.
- Use ALPHA modeling results to provide a calibration for technology package effectiveness within the LPM
- Validate ALPHA modeling results using a variety of data sources including chassis dynamometer testing of production and developmental vehicles, dynamometer testing of production engines and transmissions, HIL testing of developmental engine configurations, comparison with automobile manufacturer and Tier 1 supplier data, and comparison with peer-reviewed/published data sources.
- Update LPM calibration with validated ALPHA model technology package effectiveness.

Notable modeling updates from the Draft TAR supported by public comments include:

- EPA has updated both the ALPHA model and the LPM to calculate vehicle effectiveness based on power-to-weight ratio and road load characteristics. Baseline vehicles are mapped into these groups accordingly. Please refer to Section 2.3.3.2.2 for more information on this update.
- Engine displacement has been increased 5 percent in the OMEGA analysis for technology packages containing future Atkinson engines to account for performance and fuel characteristics.

The EPA analysis of naturally aspirated Atkinson cycle engines provides an example of an analytical framework that integrates CAE together with other methods used by EPA to evaluate future vehicle technologies. The 2.0L Mazda SKYACTIV-G engine was introduced in 2012 in the U.S. This engine represents state-of-the art brake thermal efficiency for a naturally aspirated, spark-ignition engine and is the first non-HEV application of an Atkinson cycle engine in a U.S. light-duty vehicle application. EPA conducted chassis dynamometer testing of Mazda vehicles with the SKYACTIV-G engine and also purchased versions of this engine marketed in the U.S. (13:1 geometric compression ratio) and EU (14:1 geometric compression ratio) for detailed engine dynamometer mapping and HIL testing. After both chassis dynamometer testing and initial engine dynamometer testing, EPA conducted an engineering analysis to prioritize near-term technologies that could potentially yield further brake thermal efficiency improvements, broaden areas of high thermal efficiency and/or better align high brake thermal efficiency operation with both the regulatory drive cycles and with urban driving with the goal of meeting the 2022-2025 GHG standards in a "standard car" configuration (approximately D-segment size-class).

The technologies chosen for further analysis included:

- Improving alignment of high brake thermal efficiency operation with urban driving via road load reduction, switching to an advanced 8-speed automatic transmission, and using fixed 4/2 cylinder deactivation
- Improving brake thermal efficiency by increasing expansion the ratio from 13:1 to 14:1 along with the addition of low-pressure-loop EGR for additional knock mitigation on standard pump fuel and additional pumping loss improvements

An initial proof of concept evaluation of increased expansion ratio, low-pressure-loop cooled EGR and cylinder deactivation was conducted using GT-POWER engine modeling.[554] Engine dynamometer testing with HIL simulation of regulatory drive cycles was used for concept evaluation. A 2.0L SKYACTIV-G to larger D-segment vehicles was simulated through the application of an advanced 8-speed automatic transmission and reduced road load .[555] Combinations of these technologies were also compared to similar vehicle configurations using turbocharged, downsized GDI engines using the ALPHA vehicle model.[556] An important part of EPA's use of CAE has been to validate simulation results using other data sources. For example, EPA validated the ALPHA modeling and HIL testing using chassis dynamometer test data and validated the GT-POWER modeling using engine dynamometer test data.

2.3.3.5 Lumped Parameter Model

The foundation of the technology assessments that EPA conducted for the FRM, Draft TAR, and this Proposed Determination was constructed from an evaluation of the state of individual technologies: their costs, emissions-reducing benefits, and feasibility of implementation within the time frame of the standards. As described in Chapter 2.3.3.3, data describing individual technologies were synthesized at the vehicle-level using the physics-based ALPHA model. Because specific inputs such as engine maps, transmission parameters, accessory loads, etc. are not available for every vehicle, the ALPHA model is not sufficient to generate absolute tailpipe emissions values for each vehicle in the baseline fleet using only raw technology data as an input. Instead, the incremental effectiveness values generated by the ALPHA model are used to calibrate the Lumped Parameter Model (LPM) so that the overall emissions-reducing benefits of complete technology packages can be modeled reliably for individual vehicles within each ALPHA effectiveness class. This approach of applying incremental effectiveness improvements according to vehicle class is consistent with the approach used in the FRM and Draft TAR.

For this Proposed Determination, the representativeness of those effectiveness estimates has been improved by defining effectiveness classes according to the important characteristics of power-to-weight ratio and road load horsepower, as well as updating the exemplar vehicle characteristics to align with the MY2015 fleet as described in Section 2.3.3.2.

2.3.3.5.1 Approach for Modeling Incremental Effectiveness

It is widely acknowledged that full-scale, physics-based vehicle simulation is the most thorough approach to modeling future benefits of a package of new technologies. This is especially important for quantifying the efficiency of technologies and groupings (or packages) of technologies that do not currently exist in the fleet, nor as prototypes. However, developing and executing every possible combination of technologies directly in a compliance environment using full-scale vehicle simulation, while possible, would create many thousands of vehicle combinations and corresponding effectiveness results, many of which would never be applied. For example, combinations of technologies such as continuously variable transmissions applied to pick-up trucks with towing capability are not viable using technologies that EPA expects to be available in the MY2022 to 2025 time frame.

In assessing the GHG standards, EPA analyzes a wide array of potentially feasible technology options rather than attempting to pre-select the “best” solutions. For example, in the analysis for the Draft TAR, EPA built over 800,000 packages for use in its OMEGA compliance model, which spanned 19 vehicle classes and over 2,200 baseline vehicle models. The Proposed Determination analysis has expanded the number of vehicle types to 29 and the number of baseline vehicles to over 2,000 models.

General Motors (Patton et al)[557] presented a vehicle energy balance analysis to highlight the synergies that arise with the combination of multiple vehicle technologies. This report demonstrated an alternative methodology (to vehicle simulation) to estimate these synergies, by means of a “lumped parameter” approach. This approach served as the basis for EPA’s lumped parameter model (LPM). EPA continues to believe that the lumped parameter approach is the most practical surrogate to estimate the effectiveness of technology package combinations for the Proposed Determination analysis.

The LPM does not model absolute effectiveness, but rather, the incremental improvements between vehicle technology packages calibrated by full vehicle simulation modeling. As in the FRM and Draft TAR, the LPM provides an interpolation between fully simulated vehicle packages, based on industry accepted values, in order to account for the effect of individual technologies. This increased resolution allows for every modeled technology to be accounted for to prevent double counting and/or missed opportunities for improvement.

To further explain this process, consider an engine map in a full vehicle simulation model that includes GDI+EFR1+DCP+DVVL, but the baseline vehicle only includes GDI+EFR1+DCP. As no engine map without DVVL is available, the modeler may have to apply this engine map to the baseline vehicle taking DVVL off the table for improvement. To correct for this situation, the LPM contains all of the individual components selected as a group to equal the effectiveness of the full vehicle simulated GDI+EFR1+DCP+DVVL engine map. At this point DVVL can be deselected from the LPM to match the baseline vehicle's GDI+EFR1+DCP engine, reducing the package effectiveness appropriately. Subsequently in the modeling process, DVVL is added as an improvement to the baseline engine, matching the full vehicle simulation results in the process.

The opposite situation also exists: an engine map in a full vehicle simulation model may include GDI+EFR1+DCP but the baseline vehicle may include GDI+EFR1+DCP+DVVL. As no engine map with DVVL is available, the modeler may have to apply this engine map to the baseline vehicle, leaving the baseline vehicle represented without DVVL. This would allow double counting of DVVL if this technology were added later in the vehicle improvement process. As before, the LPM contains all of the individual components selected as a group to equal the effectiveness of the full vehicle simulated GDI+EFR1+DCP engine map. At this point DVVL is individually selected from the LPM to match the baseline vehicle's GDI+EFR1+DCP+DVVL engine, increasing the package effectiveness appropriately.

AAM commented on the Draft TAR that the starting point efficiency is critically important for projecting the benefits of additional technology and that the LPM does not account for the starting point efficiency. EPA agrees with the criticality of starting point efficiency but does not agree that the LPM does not account for the starting point efficiency. EPA's methodology for establishing effectiveness starts with an assessment of the application of technology in each individual vehicle in the baseline fleet. Existing technologies within the baseline fleet are identified to avoid double counting of technology benefits. In addition, the certified CO2 performance of each vehicle, which is directly reflects a vehicle's efficiency, is the starting point for determining the incremental effectiveness of additional technology. The incremental effectiveness determined by the LPM accounts for the vehicle type, horsepower to weight ratio, road load characteristics and energy loss categories. In addition, the incremental effectiveness applied by the LPM is bounded by the calibration data from ALPHA full vehicle simulation. The details regarding each of these factors is carefully documented in the section below.

2.3.3.5.2 Calibration of LPM using ALPHA model

As in the Draft TAR, the basis for calibrating and validating the lumped parameter model for this Proposed Determination is the effectiveness data generated by the benchmarking and full-vehicle simulation modeling activities described earlier in this section. As described above, the LPM also allows benchmarked and/or simulated vehicle packages to be separated into individual components to properly account for the technologies already in the vehicle fleet, to avoid any double counting of these technologies. The lumped parameter approach was endorsed by the National Academy of Sciences in the 2015 NAS Report, which stated: "In particular, the committee notes that the use of full vehicle simulation modeling in combination with lumped parameter modeling has improved the agencies' estimation of fuel economy impacts."[558]

As described in Section 2.3.3.3.3, as part of the quality assurance process, EPA checked the ALPHA simulation results that were used to calibrate the lumped parameter model against conservation of energy requirements. Similarly, the basis for EPA's lumped parameter analysis is a first-principles energy balance that estimates the manner in which the chemical energy of the fuel is converted into various forms of thermal and mechanical energy by the vehicle. The analysis accounts for the dissipation of energy into the different categories of energy losses, including each of the following:

- Second law losses (thermodynamic losses inherent in the combustion of fuel)
- Heat lost from the combustion process to the exhaust and coolant
- Pumping losses, i.e., work performed by the engine during the intake and exhaust strokes
- Friction losses in the engine
- Transmission losses, associated with friction and other parasitic losses of the gearbox, torque converter (when applicable), and driveline
- Accessory losses, related directly to the parasitics associated with the engine accessories

- Vehicle road load (tire and aerodynamic) losses
- Inertial losses (energy dissipated as heat in the brakes)

It is assumed that each baseline vehicle has a fixed percentage of fuel lost to each category. Each technology is grouped into the major types of engine loss categories it reduces. In this way, interactions between multiple technologies that are applied to the vehicle may be determined. When a technology is applied, the lumped parameter model estimates its effects by modifying the appropriate loss categories by a given percentage. Then, each subsequent technology that reduces the losses in an already improved category has less of a potential impact than it would if applied on its own.

Using a lumped parameter approach for calculating package effectiveness provides necessary grounding to physical principles. Due to the mathematical structure of the model, it naturally limits the maximum effectiveness achievable for a family of similar technologies. This can prove useful when computer-simulated packages are compared to a "theoretical limit" as a plausibility check. Additionally, the reduction of certain energy loss categories directly impacts the effects on others. For example, as mass is reduced the benefits of brake energy recovery decreases because there is less inertia energy to recapture. In their comments on the Draft TAR, the AAM stated that "linear regression models within the LPM are not based on the first order determinants of powertrain efficiency and, therefore, do not properly capture the fundamental trends." EPA disagrees with this assessment. As stated above, the LPM is grounded in fundamental physical principles and bounded by full vehicle simulation. EPA has further refined the LPM based on some of the comments received; however, we continue to believe that the LPM provides an accurate assessment of incremental effectiveness.

EPA has updated the LPM for this Proposed Determination to improve fidelity for baseline attributes and technologies. Consistent with suggestions in the public comments, the LPM now characterizes baseline vehicles based on their power-to-weight ratio and road load characteristics (see Section 2.3.3.2 above). For this Proposed Determination, as in the Draft TAR, the LPM has been calibrated to follow the results of the ALPHA full vehicle simulation model to facilitate the vehicle package building process used in the OMEGA model.

2.3.3.5.3 Lumped Parameter Model Usage in OMEGA

The Lumped Parameter Model (LPM) is used in the OMEGA model to incrementally improve the effectiveness of vehicle models in the baseline fleet as technology packages are applied. As a first step, approximately fifty technology packages are created with increasing effectiveness for each vehicle type. Several example packages are shown in Table 2.51.

Table 2.51 Example OMEGA Vehicle Technology Packages (values are for example only)

Package #	Technology Package	Technology Package Effectiveness
0	4-Speed Auto	0%
1	6-Speed Auto	4%
2	8-Speed Auto + DCP	10%
10	8-Speed + DCP + TURB24	20%
20	8-Speed + DCP + Aero2 + TURB24 + 10%MR	28%

Step two selects the next vehicle in the baseline fleet and applies all fifty technology packages in sequence, using the LPM to calculate incremental effectiveness values at each step. As the technologies in the baseline vehicles have been tabulated based on publicly available data, the incremental effectiveness improvement will not include these baseline vehicle technologies, to avoid double counting. Table 2.52 contains an example baseline vehicle. Table 2.53 illustrates the package application process.

Table 2.52 Example Baseline Vehicle (values are for example only)

Baseline Vehicle Technologies	Baseline Vehicle Effectiveness
6-Speed Auto + DCP	6%

Table 2.53 Example Package Application Process (values are for example only)

Package #	Technology Package	Technology Package Effectiveness	Resulting Vehicle Incremental Effectiveness
0	4-Speed Auto	0%	0%
1	6-Speed Auto	4%	0%
2	8-Speed Auto + DCP	10%	3%
10	8-Speed + DCP + TURB24	20%	11%
20	8-Speed + DCP + Aero2 + TURB24 + 10%MR	28%	17%

As shown, the incremental effectiveness is not simply additive, as the LPM (following the ALPHA model) takes into account synergies and dis-synergies between the existing and applied technologies. This process also enables the OMEGA model to assign baseline vehicles a cost to represent their existing technologies and calculate an incremental cost to match with the incremental effectiveness as each technology package is applied. The completed technology package effectiveness values from the LPM are compared to the corresponding ALPHA full vehicle simulation model results as a final check before they are used in the OMEGA model. An example subset of calibration points is shown in Table 2.54. This calibration process is an important step to ensure that full vehicle simulation results from the ALPHA model are used as the primary effectiveness inputs to the OMEGA model.

Table 2.54 Example Subset of ALPHA/LPM Calibration Check Points for Vehicle Type 1

Technology Package	Mass	Aero	Roll	ALPHA Effectiveness from Reference Package	LPM Effectiveness from Reference Package	Delta Effectiveness
LUB+EFR1+DCP+SGDI +6AT+HEG1+EPS+IACC1	0%	0%	0%	0.0%	0.0%	0.0%
LUB+EFR1+DCP+SGDI +8AT+HEG1+EPS+IACC1	0%	0%	0%	7.0%	7.0%	0.0%
LUB+EFR2+ATK2+DCP +SGDI+6AT+HEG1+EPS+IACC1	0%	0%	0%	5.0%	4.9%	-0.1%

LUB+EFR2+ATK2+DCP +SGDI+8AT+HEG1+EPS+IACC1	0%	0%	0%	12.1%	12.0%	-0.1%
LUB+EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT+HEG2 +EPS+IACC2	0%	0%	0%	25.8%	25.7%	-0.1%
LUB+EFR2+TURB24 +CEGR+DEAC+DCP +SGDI+8AT+HEG2+EPS+IACC2	0%	0%	0%	21.2%	21.0%	-0.2%
LUB+EFR2+ATK2+CEGR +DEAC+DCP+SGDI+8AT+HEG2 +EPS+IACC2	10%	20%	20%	36.6%	36.5%	-0.1%

The complete list of baseline fleet vehicles, each incremented approximately fifty times, results in approximately 160,000 improved vehicles as input to the OMEGA model.

The effectiveness reductions and costs that are associated with applying a technology will depend on the starting point technologies from which the cost and effectiveness improvements are measured. For example, two vehicle models that start with different packages of technologies will likely have different costs and effectiveness, even if both models finally arrive at the same package combination of technologies. EPA's recognition of the importance of clearly specifying the point of comparison for cost and effectiveness estimates is consistent with the NAS committee's finding "that understanding the base or null vehicle, the order of technology application, and the interactions among technologies is critical for assessing the costs and effectiveness for meeting the standards."

As long as the point of comparison is maintained consistently throughout the analysis for both the baseline and future fleets, the decision of where to place an origin along the scale of cost and effectiveness is inconsequential. For EPA's technology assessment, the origin is defined to coincide with a "null technology package," which represents a technology floor such that all technology packages considered in this assessment will have equal or greater effectiveness, consistent with the Draft TAR approach. While other choices would have been equally valid, this definition of a "null package" has the practical benefits of avoiding technology packages with negative effectiveness values, while also allowing for a direct comparison of effectiveness assumptions with those of the Draft TAR.

2.3.3.5.4 Appropriateness of LPM Effectiveness Modeling for the Overall Fleet

In addressing EPA's modeling methodology, several stakeholders submitted comments critical of the LPM. The most pointed claims were aimed at the fundamental validity of using any tool other than full vehicle simulation for the compliance analysis, with commenters contending that "…continued use of the LPM is not an adequate or accurate tool to assess the efficacy of fuel economy technologies applied to a wide variety of vehicles." (pg. A-11, Global Automakers), and "The linear regression models within the LPM are not based on the first order determinants of powertrain efficiency and, therefore, do not properly capture the fundamental trends." (pg. 35, Alliance), and "the core issue with the agencies' technology effectiveness over-projections is rooted in the 0-D LPM model itself." (Attachment 2, pg. 45, Alliance.)

EPA disagrees that the LPM, when utilized as intended, makes inaccurate predictions. The LPM's effectiveness estimates are reliable due both to their basis in fully simulated vehicle packages, as well as to the physical principles applied to interpolate between simulated packages. Specifically, the use of energy loss categories within the LPM ensures that the combined benefits of multiple technologies in a package are not double counted when two technologies are competing to reduce the same loss. EPA continues to believe that as in the Draft TAR (as well as in the 2012-2016 standards rulemaking, and the 2017-2025 rulemaking), when used as intended within the bounds of the calibration, the LPM is an appropriate tool for assessing the effectiveness of advanced technology packages for this Proposed Determination.

EPA's assessment is also supported by both the 2010 and the 2015 studies published by the National Academy of Science – for example, in the 2015 report, the NAS stated, "The committee notes that the use of full vehicle simulation modeling in combination with lumped parameter modeling and teardown studies contributed substantially to the value of the Agencies' estimates of fuel consumption and costs, and it therefore recommends they continue to increase the use of these methods to improve their analysis."[EEE] Note that both the 2010 and the 2015 NAS Committees specifically evaluated earlier versions of the EPA-developed LPM that informed the Committee's findings and recommendations.

In comments submitted on the Draft TAR, the Alliance stated that EPA's modeling processes "do not recognize the inherent variability of efficiency within the light-duty fleet, treating all products within a category as equal" and recommended that the "LPM should be enhanced and upgraded to incorporate the key vehicle and powertrain parameters which determine powertrain efficiency." While the degree of resolution in EPA's effectiveness modeling in the FRM and Draft TAR was sufficient to distinguish between individual models, and to enable the application of unbiased effectiveness estimates within a reasonably narrow range, EPA has taken several steps for this Proposed Determination in response to the recommendation from commenters that the precision of the effectiveness modeling be further improved. First, and most significantly, as described in Chapter 2.3.3.2, EPA has refined the ALPHA classes used for grouping vehicles according to the attributes that most directly influence technology effectiveness: namely power-to-weight ratio and road load horsepower. As discussed in that chapter, this refinement has significantly reduced the variation between vehicles in each ALPHA class, thus improving the precision of the modeling. As an additional refinement, EPA has also incorporated the consideration of each individual vehicle's power-to-weight ratio into the effectiveness numbers produced by the LPM. Using a set of relationships between power-to-weight ratio and effectiveness produced by the ALPHA model, EPA is now applying an effectiveness adjustment in the OMEGA process based on the deviation in the power-to-weight value from the exemplar vehicle in that class, as illustrated above in Figure 2.90 using the coefficients in Table 2.55 and Equation 3.

Table 2.55: Parameters for Power-to-Weight Adjustment of Effectiveness Values in OMEGA

		Lower PW Range	Mid/Upper PW Range	Upper PW Range (HPW only)

[EEE] See Finding 8.7 and 10.12 and Recommendation 8.3 of "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles published by the Committee on the Assessment of Technologies for Improving Fuel Economy of Light-duty Vehicles"; Phase 2; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Research Council, ISBN 978-0-309-37388-3, 2015. See also Chapter 8 (page 118) of "Assessment of Fuel Economy Technologies for Light-Duty Vehicles"; Committee on the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy; National Research Council; ISBN 978-0-309-15607-3, 2010.

ALPHA Class	Eng Tech	PW Cutoff ≤ (hp/100lb)	m	b (*1e2)	PW Cutoff > (hp/100lb)	m	b (*1e2)	PW Cutoff ≥ (hp/100lb)	m	b (*1e2)
LPW_LRL	Turbo*	419	1.2	4.19	4.19	1.2	4.19	-	-	-
	ATK2	4.19	-0.6	4.19	4.19	-1.0	4.19	-	-	-
	ATK2+cEGR	4.19	1.2	4.19	4.19	1.0	4.19	-	-	-
MPW_LRL	Turbo*	5.25	1.8	5.25	5.25	1.8	5.25	-	-	-
	ATK2	5.25	-0.5	5.25	5.25	-0.5	5.25	-	-	-
	ATK2+cEGR	5.25	1.2	5.25	5.25	1.0	5.25	-	-	-
HPW	Turbo*	7.14	2.0	7.14	7.14	1.6	7.14	11.0	0.8	3.29
	ATK2	7.14	-1.4	7.14	7.14	-0.5	7.14	11.0	-0.2	1.36
	ATK2+cEGR	7.14	1.0	7.14	7.14	0.6	7.14	11.0	0.2	-0.568
LPW_HRL	Turbo*	4.46	1.5	4.46	4.46	1.5	4.46	-	-	-
	ATK2	4.46	-0.6	4.46	4.46	-1.0	4.46	-	-	-
	ATK2+cEGR	4.46	1.2	4.46	4.46	1.0	4.46	-	-	-
MPW_HRL	Turbo*	5.68	2.0	5.68	5.68	2.0	5.68	-	-	-
	ATK2	5.68	-0.5	5.68	5.68	-0.5	5.68	-	-	-
	ATK2+cEGR	5.68	1.2	5.68	5.68	1.0	5.68	-	-	-
Truck	Turbo*	6.10	2.0	6.10	6.10	2.0	6.10	-	-	-
	ATK2	6.10	-0.7	6.10	6.10	-0.7	6.10	-	-	-
	ATK2+cEGR	6.10	1.2	6.10	6.10	1.0	6.10	-	-	-

*Note: Turbocharged Miller Cycle engines are classified as turbocharged

Equation 3. Effectiveness adjustment relative to exemplar

Effectiveness Adjustment, relative to exemplar = m(PW-b)

To illustrate how each individual vehicle's power-to-weight ratio is accounted for in the effectiveness estimates used in the OMEGA process, an example of a vehicle in the HPW ALPHA class is provided here (Baseline Index 2264). For that vehicle, a technology package with a turbocharged engine (TP06) is applied in the OMEGA model's compliance analysis of the 2025 standards. The baseline vehicle's power-to-weight ratio (*PW*) of 6.92 hp/100lb is less than the 7.14 hp/100lb value for the exemplar vehicle in that class (as defined in Table 2.47), indicating that some effectiveness adjustment may be justified. Applying Equation 3 and the Turbo technology values of m = 2.0 and b = 7.14 hp/100lb from Table 2.55, an adjustment of -0.44% (reduction in effectiveness) is applied for this technology package, relative to the effectiveness value produced by the LPM for the HPW exemplar vehicle.

Comments received on the Draft TAR also focused on the processes used by EPA to assure the reliability and accuracy of the modeling tools. The Alliance stated that "[N]o procedure or methodology is currently in place to check the outcomes of the [LPM's] technology effectiveness projection process against logical efficiency metrics and limits. Without such checks, the outcomes can exceed plausible limits" (pg. 44, Alliance comments). EPA does not agree that the processes used for the Draft TAR did not involve plausibility checks. The LPM has been calibrated to, and is bounded by, ALPHA Full Vehicle Simulation Model results. It was not used to predict anything beyond the bounds of these fundamental inputs. The specific plausibility limits recommended by the Alliance are based on a top-down empirical analysis of existing vehicles, and do not reflect the fundamental efficiency improvements that are enabled through physical technology changes in the future fleet. For the reasons described further in

Appendix A, EPA is not considering any of the plausibility limits imposed by the three metrics proposed by the Alliance. At the same time, EPA agrees that quality assurance processes are important for ensuring the validity of any modeling. For this Proposed Determination, EPA has adopted one of the quality assurance tools recommended in the Alliance-contracted report.

Using the methodology described in TSD Appendix B, EPA has calculated a measure of powertrain efficiency, defined as the ratio of the tractive work done to move a vehicle over the test cycle to the fuel energy utilized over the same cycle. Figure 2.98 shows the production-weighted distribution of powertrain efficiencies for gasoline-fueled vehicles in the MY2015 fleet, excluding vehicles equipped with electrified powertrains. Stop-start technology, while an effective technology for reducing emissions, is also excluded from the following figure and discussions, since its benefits are independent of powertrain operation efficiency.

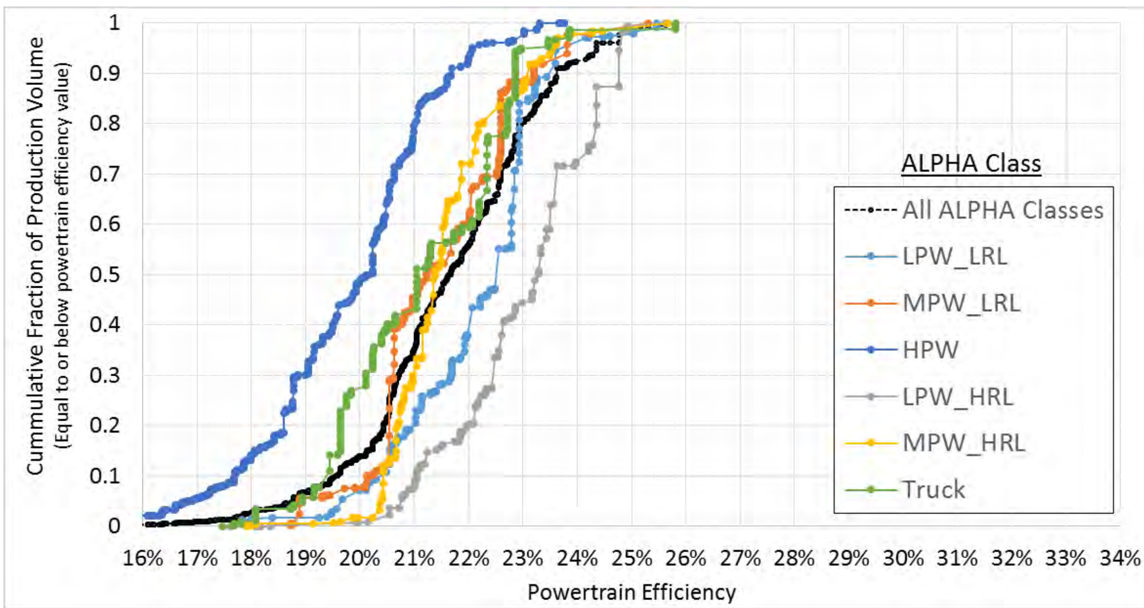


Figure 2.98 Distribution of Gasoline Powertrain Efficiencies for Vehicles in MY2015

Using the same selection criteria (i.e. gasoline engines, excluding stop-start) for the technology packages applied in the OMEGA model's compliance analysis of the MY2025 GHG standards, the powertrain efficiencies shown in Figure 2.99 are, in general, higher than the powertrain efficiencies of the MY2015 baseline fleet, as would be expected from the application of advanced technology packages.

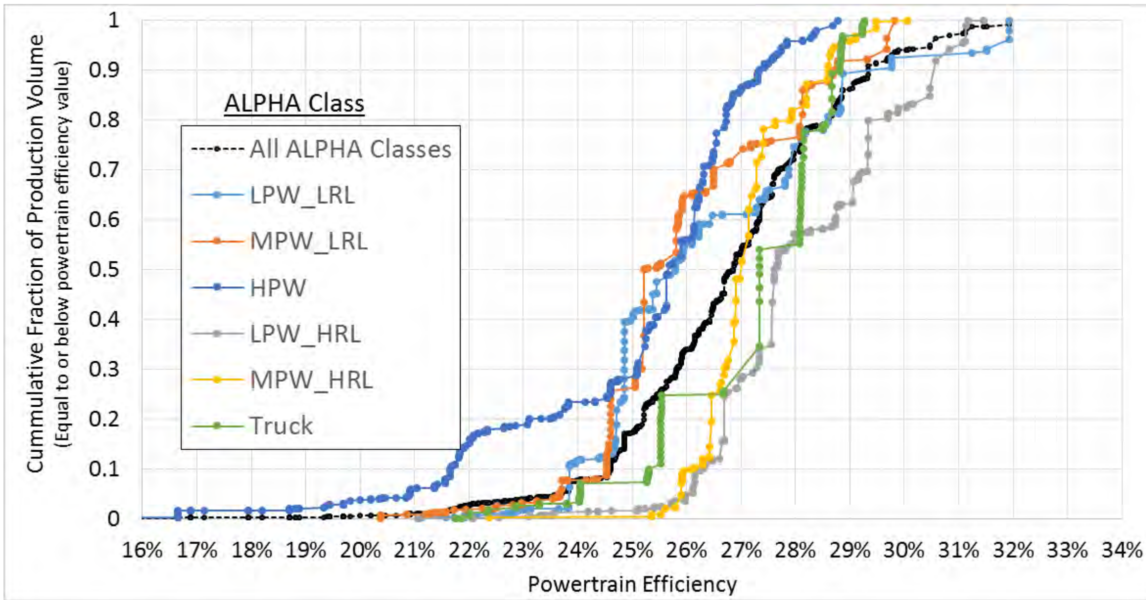


Figure 2.99 Distribution of Gasoline Powertrain Efficiencies for Vehicles in the OMEGA Compliance Analysis for MY2025 Standards

As shown in Table 2.56, the fleet median (production weighted) powertrain efficiency for gasoline non-stop-start vehicles increases from 21.6 percent in the MY2015 baseline fleet, to 26.8 percent in EPA's compliance analysis for the fleet meeting MY2025 standards. Contrary to the assertion made by The Alliance in comments to the Draft TAR that EPA's modeling processes "do not recognize the inherent variability of efficiency within the light-duty fleet, treating all products within a category as equal," the fleet produced by OMEGA's cost-minimizing compliance pathway is similar to the MY2015 baseline fleet in the degree of diversity in powertrain efficiencies among vehicles, as indicated by both the similarities in ranges between the minimum and maximum efficiencies, and the shapes of the distributions.

Table 2.56 Summary Statistics for Powertrain Efficiencies in MY2015 Baseline and OMEGA Compliance Analysis of MY2025 Standards

ALPHA Class	MY2015 Baseline Fleet			OMEGA Compliance Fleet Meeting MY2025 Standards		
	Median	Std. Dev.	min-max	Median	Std. Dev.	min-max
LPW_LRL	22.1	1.3	17.8-25.5	26.5	2.3	21.1-31.9
MPW_LRL	21.5	1.3	18.7-25.3	26.0	1.9	20.4-29.8
HPW	19.8	1.6	11.5-23.8	25.1	2.3	13.9-28.8
LPW_HRL	22.9	1.4	17.6-25.6	28.2	1.7	21.1-31.5
MPW_HRL	21.6	1.1	17.9-25.7	27.2	0.9	22.4-30.0
Truck	22.1	1.3	17.5-25.8	27.2	1.5	21.8-29.3
Fleet	**21.6**	**1.7**	**11.5-25.8**	**26.8**	**2.1**	**13.9-31.9**

Table 2.57 shows the vehicles and technology packages with the highest powertrain efficiencies modeled in EPA's 2025 compliance analysis. EPA does not believe that for this relatively small portion of the fleet (comprising approximately 6 percent of the volume of gasoline non-stop-start packages in the compliance analysis for MY2025 standards) that

powertrain efficiency values greater than 30 percent indicate a systemic overestimation of technology effectiveness.

With the exception of only two vehicles, the majority of future technology packages with high powertrain efficiencies in MY2025 are associated with vehicles that had high efficiencies in the MY2015 baseline. There are several possible explanations for this. First, although EPA's technology assessment accounts for the presence of efficiency technologies in the baseline file, there is insufficient data available to model the exact technologies applied to each individual vehicle. Because EPA has selected baseline technology parameters that are representative of typical MY2015 vehicles (e.g. based on benchmarking of current ATK2 and GDI engines, current transmissions, as well as characterization of road load technologies) the characterization of baseline technologies in this Proposed Determination will not systemically over- or under-estimate the incremental effectiveness of advanced technology packages. However, just as it is possible that some baseline vehicles will have less effective technology implementations than is typical of other vehicles in the MY2015 fleet, it is also possible that the vehicles shown in Table 2.57 may have more efficient technology implementation than is typical. Second, it is also possible that when grouping vehicles together for certification, an OEM's application of road load coefficients, ETW values, and emissions levels may be representative overall of the certified model type, but deviate from the actual values for a particular vehicle. Any discrepancies between the parameters used to calculate tractive energy (ETW, road load coefficients) and the measured fuel consumption over the test cycle would potentially result in high baseline powertrain efficiencies, and thus carry-over into high powertrain efficiencies of future technology packages. Again, this variation would not tend to result in a systemic over- or under-estimation of effectiveness.

Table 2.57 Summary Statistics for Powertrain Efficiencies in MY2015 Baseline and OMEGA Compliance Analysis of MY2025 Standards

				MY2025 Compliance Analysis		MY2015 Baseline	
ALPHA Class	Baseline Index	Tech Pkg.	Model	Powertrain Efficiency	Percentile (in class)	Powertrain Efficiency	Percentile (in class)
LPW_LRL	1561	TP08	Veloster	31.5%	93.8%	23.1%	85.0%
	1510	TP08	Elantra	31.9%	100.0%	22.8%	58.2%
LPW_HRL	1737	TP08	CX-5 4WD	31.5%	100.0%	24.8%	87.4%
	2056	TP10	City Express Cargo Van	30.2%	83.2%	24.0%	72.3%
	2151	TP10	NV200 Cargo Van	30.1%	83.0%	24.0%	72.0%
	1371	TP08	TERRAIN FWD	31.2%	99.9%	23.3%	55.4%
	1220	TP08	EQUINOX FWD	31.1%	98.9%	23.3%	54.1%
	1180	TP08	CAPTIVA FWD	31.1%	95.6%	23.3%	50.8%
	2304	TP08	RAV4 Limited AWD	30.8%	94.2%	22.7%	40.6%
	2286	TP08	HIGHLANDER	30.0%	82.5%	22.3%	26.1%
MPW_HRL	733	TP07	EXPLORER FWD	30.0%	100.0%	24.5%	98.4%

Table 2.58 shows a selection of vehicles throughout the distribution of powertrain efficiencies in the OMEGA compliance analysis for the MY2025 standards. For this Proposed Determination, EPA has incorporated the powertrain efficiency metric into the effectiveness modeling Quality Control processes in order to identify possible anomalies in how the effectiveness estimates generated by the ALPHA physics-based model are represented in the

LPM and OMEGA process. For each of the six ALPHA classes, six vehicles were chosen throughout the distribution of powertrain efficiencies; including the vehicle with maximum powertrain efficiency in each class (i.e. 100th percentile).

Table 2.58 Powertrain Efficiencies by ALPHA Class from MY2025 OMEGA Compliance Analysis

Approx. Percentile (in class)	ALPHA Class	Baseline Index	Model	Tech Pkg	Percentile (in class)	Powertrain Efficiency
10	HPW	1012	MUSTANG	TP07	7.70%	21.60%
	LPW_HRL	2193	IMPREZA	TP05	5.20%	26.10%
	LPW_LRL	2277	COROLLA	TP05	10.50%	23.80%
	MPW_HRL	1707	Sorento FWD	TP09	0.80%	25.40%
	MPW_LRL	1414	ACCORD	TP07	10.10%	24.50%
	Truck	773	F150 PICKUP 2WD	TP05	9.90%	25.30%
25	HPW	1423	ACCORD	TP06	26.50%	24.60%
	LPW_HRL	1556	Tucson AWD	TP12	11.60%	26.40%
	LPW_LRL	1443	CIVIC	TP06	31.90%	24.90%
	MPW_HRL	1494	ODYSSEY 2WD	TP06	24.70%	26.50%
	MPW_LRL	1403	ACCORD	TP07	24.10%	24.60%
	Truck	2124	FRONTIER 2WD	TP08	25.00%	26.70%
50	HPW	2149	MURANO AWD	TP08	51.00%	25.70%
	LPW_HRL	2044	OUTLANDER 2WD	TP10	57.40%	28.10%
	LPW_LRL	1785	MAZDA3 5-Door	TP05	52.80%	25.90%
	MPW_HRL	711	ESCAPE AWD	TP07	43.90%	26.90%
	MPW_LRL	1687	OPTIMA	TP09	28.00%	25.10%
	Truck	2132	FRONTIER 2WD	TP05	54.00%	27.30%
75	HPW	1380	MDX 4WD	TP07	77.30%	26.50%
	LPW_HRL	1483	CR-V 4WD	TP08	76.50%	29.30%
	LPW_LRL	1510	Elantra	TP07	68.00%	27.80%
	MPW_HRL	1498	PILOT 4WD	TP06	62.00%	27.10%
	MPW_LRL	695	EDGE FWD	TP07	74.90%	27.20%
	Truck	2316	TACOMA 2WD	TP06	74.20%	28.10%
90	HPW	1122	CTS SEDAN AWD	TP08	87.30%	27.20%
	LPW_HRL	2302	RAV4 AWD	TP08	91.90%	30.60%
	LPW_LRL	1661	Forte	TP08	90.40%	29.80%
	MPW_HRL	2236	NX 200t	TP07	88.10%	28.60%
	MPW_LRL	1665	Forte	TP08	88.00%	28.60%
	Truck	2324	TACOMA 2WD	TP05	84.20%	28.70%
100	HPW	1369	TERRAIN AWD	TP08	100.00%	28.80%
	LPW_HRL	1738	CX-5 4WD	TP08	100.00%	31.50%
	LPW_LRL	1510	Elantra	TP08	100.00%	31.90%

	MPW_HRL	733	EXPLORER FWD	TP07	100.00%	30.00%
	MPW_LRL	1555	Sonata SPORT/LIMITED	TP08	100.00%	29.80%
	Truck	1319	CANYON 2WD	TP08	96.90%	28.90%

For each of the vehicles modeled using the LPM and OMEGA process shown in Table 2.58, EPA applied the ALPHA model using the road load coefficients, rated horsepower, and ETW of the MY2015 baseline vehicle, along with the technologies corresponding to the TP00 technology package. The ALPHA model was then used to represent the future technology packages shown in Table 2.58, including the related mass reduction and reductions in road loads relative to the baseline package. The results, shown in Figure 2.100, confirm that the LPM is able to reliably replicate the effectiveness values generated by the physics-based ALPHA model (within 2%) over a wide range of vehicle classes, technologies, and powertrain efficiency values.

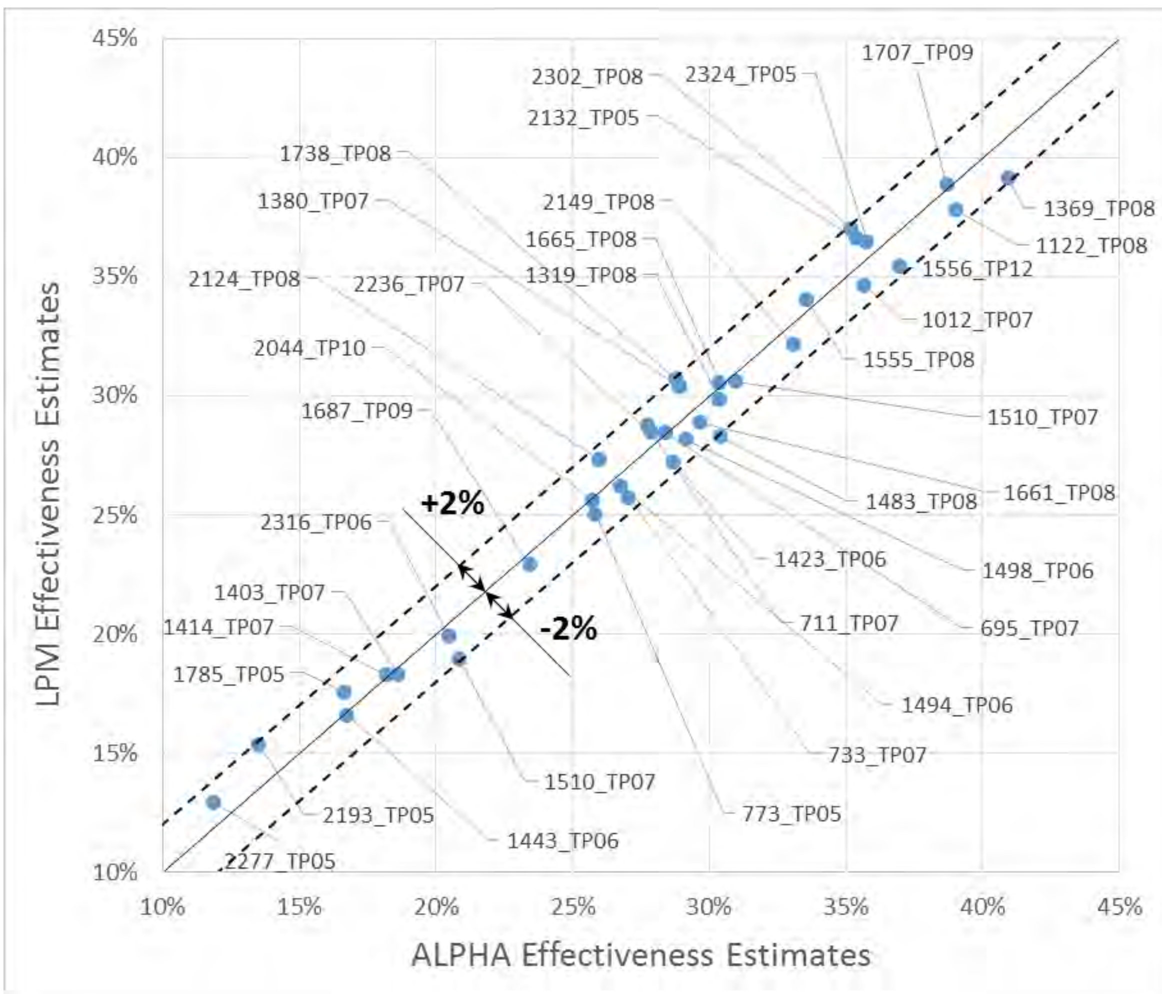


Figure 2.100 LPM and ALPHA Package Effectiveness Comparison for Vehicles and Throughout Distribution of Powertrain Efficiencies

2.3.4 Data and Assumptions Used in the GHG Assessment

2.3.4.1 Engines: Data and Assumptions for this Assessment

The majority of engine technologies used in this assessment are detailed in Chapter 2.2 of this TSD. This section details engine technology information specific to the Proposed Determination analysis.

In an effort to characterize the efficiency and performance of late model vehicle powertrains, and to update our engine data from that used in the FRM and Draft TAR, EPA tested several engines at its National Vehicle and Fuel Emissions Laboratory (NVFEL) and contractor facilities. Depending on the information required, the engines were tested with their factory and/or developmental engine management systems that allowed EPA engineering staff to calibrate engine control parameters. Figure 2.101 illustrates a typical engine test.

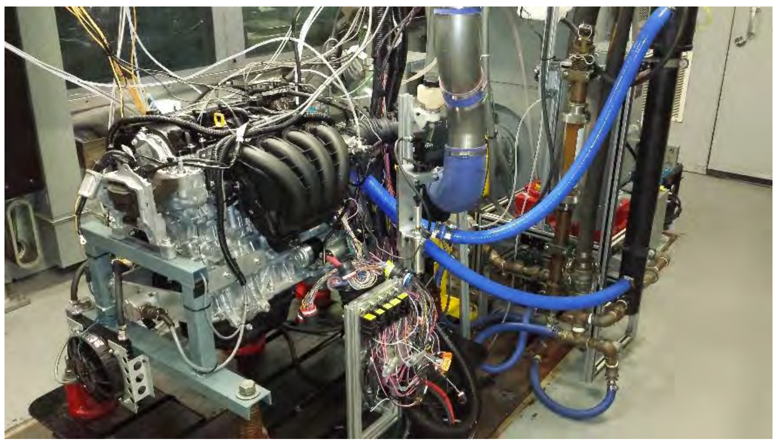


Figure 2.101 2.0L I4 Mazda SKYACTIV-G Engine Undergoing Engine Dynamometer Testing at the EPA-NVFEL Facility.

In some cases, future engine configurations can be modeled using engine simulation software. EPA used Gamma Technologies GT-POWER engine simulation software to model future engine configurations based upon the Mazda 2.0L I4 SKYACTIV-G. Computer-aided engineering tools, including GT-POWER, are commonly used during the initial stages of product development by automotive manufacturers and academia to establish the potential performance of engine design features, with respect to efficiency, emissions, and performance. GT-POWER is a physics based suite of software that combines predictive diesel or spark-ignition combustion models; CAD-based, preprocessed libraries of the physical layout of induction, exhaust and combustion systems; models of chemical kinetics; wave dynamics models; turbocharger turbine and compressor models with surge, reverse-flow and pressure wave prediction; induction turbulence models; a kinetic knock model; injector spray models and an ability to apply minor adjustments to model-predicted parameters using data from engine dynamometer measurements. Engine dynamometer data was also used to directly validate simulations of specific engine hardware configurations via comparisons of measured vs. modeled values for knock intensity, combustion phasing, FMEP, BTE and other parameters.

2.3.4.1.1 Low Friction Lubricants (LUB)

There were no public comments received with supporting data that would provide basis for changing the cost or effectiveness estimates for this technology, nor has EPA found additional information that supports such a change since the Draft TAR. Based on the analysis for the Draft TAR, the agencies estimated the effectiveness of LUB to be 0.5 to 0.8 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Proposed Determination.

The cost associated with making the engine changes needed to accommodate low friction lubes is equivalent to that used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.59 Costs for Engine Changes to Accommodate Low Friction Lubes (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$3	1	$3	$3	$3	$3	$3	$3	$3	$3	$3
IC	Low2	2018	$1	$1	$1	$1	$1	$1	$1	$1	$1
TC			$4	$4	$4	$4	$4	$4	$4	$4	$4

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.2 Engine Friction Reduction (EFR1, EFR2)

There were no public comments received with supporting data that would provide basis for changing the cost or effectiveness estimates for this technology, nor has EPA found additional information that supports such a change since the Draft TAR. Based on the analysis for the Draft TAR, EPA estimated the effectiveness of EFR1 at 2.0 to 2.7 percent. Based on the analysis for the Draft TAR, EPA estimated the effectiveness of EFR2 at 3.4 to 4.8 percent. EPA has reviewed this technology and finds the effectiveness estimate remains applicable for this Proposed Determination.

The costs associated with engine friction reduction are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs are shown below first for engine friction reduction level 1 and then for level 2.

Table 2.60 Costs for Engine Friction Reduction Level 1 (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$38	1	$38	$38	$38	$38	$38	$38	$38	$38	$38
I4	DMC	$51	1	$51	$51	$51	$51	$51	$51	$51	$51	$51
V6	DMC	$77	1	$77	$77	$77	$77	$77	$77	$77	$77	$77
V8	DMC	$102	1	$102	$102	$102	$102	$102	$102	$102	$102	$102
I3	IC	Low2	2018	$9	$9	$7	$7	$7	$7	$7	$7	$7
I4	IC	Low2	2018	$12	$12	$10	$10	$10	$10	$10	$10	$10
V6	IC	Low2	2018	$19	$19	$15	$15	$15	$15	$15	$15	$15
V8	IC	Low2	2018	$25	$25	$20	$20	$20	$20	$20	$20	$20
I3	TC		2018	$48	$48	$46	$46	$46	$46	$46	$46	$46
I4	TC		2018	$63	$63	$61	$61	$61	$61	$61	$61	$61
V6	TC		2018	$95	$95	$91	$91	$91	$91	$91	$91	$91
V8	TC		2018	$127	$127	$122	$122	$122	$122	$122	$122	$122

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.61 Costs for Engine Friction Reduction Level 2 (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$84	1	$84	$84	$84	$84	$84	$84	$84	$84	$84

I4	DMC	$109	1	$109	$109	$109	$109	$109	$109	$109	$109	$109
V6	DMC	$160	1	$160	$160	$160	$160	$160	$160	$160	$160	$160
V8	DMC	$211	1	$211	$211	$211	$211	$211	$211	$211	$211	$211
I3	IC	Low2	2024	$20	$20	$20	$20	$20	$20	$20	$20	$16
I4	IC	Low2	2024	$26	$26	$26	$26	$26	$26	$26	$26	$21
V6	IC	Low2	2024	$39	$39	$39	$39	$39	$39	$39	$39	$31
V8	IC	Low2	2024	$51	$51	$51	$51	$51	$51	$51	$51	$41
I3	TC		2024	$104	$104	$104	$104	$104	$104	$104	$104	$100
I4	TC		2024	$135	$135	$135	$135	$135	$135	$135	$135	$130
V6	TC		2024	$199	$199	$199	$199	$199	$199	$199	$199	$191
V8	TC		2024	$262	$262	$262	$262	$262	$262	$262	$262	$252

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.3 Cylinder Deactivation (DEAC)

In the Draft TAR analysis, EPA estimated an effectiveness of 3.9 to 5.3 percent for fixed cylinder deactivation.

In comments on the Draft TAR, UCS commented that EPA's effectiveness estimates for DEAC appeared conservative and cited a recent paper by ICCT that estimated fixed cylinder deactivation effectiveness as high as 6.5 percent. However, UCS also commented that NHTSA's estimate of 5 to 9 percent incremental effectiveness (on an engine already having VVT, VVL, and stoichiometric GDI) may be too aggressive.

EPA notes that our estimated effectiveness applies to fixed cylinder deactivation and is within the 3 to 7 percent range that ICCT notes was cited in the Draft TAR. While consideration of more advanced rolling dynamic systems (such as those under development by Schaeffler and Tula) might likely increase the estimated effectiveness, EPA notes that the system costs for fixed systems are lower. Rolling dynamic systems were not used by EPA to build packages for this analysis.

In their comments, FCA asserted that EPA was overly optimistic on relying on the availability of cylinder deactivation (DEAC) at unrealistic speed / load operating points. EPA based the speed and load operating points and availability of cylinder deactivation primarily upon benchmarking of a production MY2015 General Motors "Ecotec3" V6 naturally aspirated GDI light-truck engines equipped with coupled cam phasing and cylinder deactivation. The resulting effectiveness estimates based upon this data are somewhat conservative and within the lower range of effectiveness within published literature.[559,560] Over the range of engine speed (approximately 1000 to 3000 rpm) and BMEP (approximately 1 to 5 bar), effectiveness was further reduced to reflect that cylinder deactivation could not occur 100 percent of the time within the area that it is active. It was assumed that cylinder deactivation would only occur 60 percent of the time within the engine speed and BMEP window where cylinder deactivation was active. Again, this was a conservative estimate based upon benchmarking of the MY2015 General Motors "Ecotec3" V6. It did not take into consideration further improvements in NVH abatement under development to increase the percentage of vehicle operation under which cylinder deactivation can be enabled which would reasonably be expected to be in production for MY2022-MY2025 vehicles.[560]

AAM provided no data on the range of engine speeds, BMEP or other factors impacting availability of DEAC, nor did AAM provide any specific critique regarding how EPA conducted the benchmarking of the production General Motors engine equipped with DEAC. AAM also did not discuss technologies under advanced stages of development to improve the availability of DEAC (NVH abatement measures for fixed and dynamic DEAC), as discussed by EPA within the draft TAR. Consequently, EPA has been presented with no valid basis for changing its efficiency estimate for DEAC.

AAM and FCA commented that DEAC should not be applied in conjunction with cooled EGR on ATK2 engines and that the effectiveness that EPA assumed for DEAC when applied to turbo-charged downsized engines was too high. Neither FCA nor AAM provided any data or detailed description of why DEAC could not be applied in conjunction with cEGR on ATK2 engines.

EPA notes that the effectiveness that EPA assumes for DEAC applied to turbocharged, downsized I3 and I4 engines is comparable to the effectiveness demonstrated by Ford and Schaeffler for applying fixed DEAC to a turbocharged I3 engine in a paper presented at the 2015 Vienna Motor symposium.[560] Mazda also presented data at the 2015 Vienna Motor Symposium showing data from a SKYACTIV-G DEAC system at an advanced stage of development and has already publicly shared data on a version of the SKYACTIV-G engine with cylinder deactivation[561,562] with effectiveness comparable to EPA estimates for applying DEAC to ATK2, and has discussed the future application of cylinder deactivation to their SKYACTIV-G engines with the automotive press.[563,564] Engine modeling by EPA and initial hardware testing appear to show synergies between the use of cEGR and DEAC with Atkinson Cycle engines. Mazda has used cEGR with previous applications of their SKYACTIV-G engine and cEGR is currently used by Toyota and Hyundai in Atkinson Cycle engines for both HEV and non-HEV applications. VW has already introduced a 4-cylinder Miller Cycle engine, the EA211 TSI® evo, which combines DEAC, cEGR, EIVC and turbocharging.

EPA has reviewed this information and the comments submitted. It is our assessment that the effectiveness estimates used in the Draft TAR analysis for DEAC remain appropriate for this Proposed Determination analysis.

The costs associated with cylinder deactivation for this Proposed Determination analysis are shown in Table 2.62 and are equivalent to those used in the Draft TAR but updated to 2015 dollars. .

Table 2.62 Costs for Cylinder Deactivation (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I4	DMC	$88	24	$85	$83	$81	$80	$79	$78	$77	$76	$75
V6	DMC	$157	24	$150	$147	$145	$142	$140	$138	$136	$134	$133
V8	DMC	$177	24	$169	$166	$163	$160	$158	$155	$153	$151	$149
I4	IC	High1	2018	$50	$49	$30	$30	$30	$30	$30	$30	$30
V6	IC	Med2	2018	$61	$60	$45	$45	$45	$45	$45	$45	$45
V8	IC	Med2	2018	$68	$68	$51	$51	$51	$51	$51	$50	$50
I4	TC			$134	$132	$112	$110	$109	$108	$107	$106	$105
V6	TC			$211	$208	$190	$187	$185	$183	$181	$179	$177
V8	TC			$237	$234	$214	$211	$208	$206	$204	$202	$200

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.4 *Intake Cam Phasing (ICP)*

Within the analysis for the Draft TAR, EPA estimated an effectiveness of 2.1 to 2.7 percent for ICP. Toyota commented that EPA's estimate of ICP effectiveness is too high because "ICP effectiveness differs from combination of engine displacement, road load (R/L), T/M, and open duration setting of intake air camshaft." However, the comment did not share specific data on engines, specific camshaft phasing hardware and resultant effectiveness relative to hardware used, making it difficult to further assess the claim. EPA notes that the effectiveness data used in the Draft TAR is consistent with published and peer-reviewed data cited in the FRM, the Draft TAR and this Proposed Determination, and reflects performance consistent with the range of authority for ICP and DCP hardware for which cost estimates were developed. EPA therefore believes that the effectiveness estimate used in the Draft TAR remains applicable for this Proposed Determination.

The costs associated with intake cam phasing are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.63 Costs for Intake Cam Phasing (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$42	24	$40	$39	$38	$38	$37	$37	$36	$36	$35
OHC-V	DMC	$84	24	$80	$78	$77	$76	$74	$73	$72	$71	$70
OHV-V	DMC	$42	24	$40	$39	$38	$38	$37	$37	$36	$36	$35
OHC-I	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
OHC-V	IC	Low2	2018	$20	$20	$16	$16	$16	$16	$16	$16	$16
OHV-V	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
OHC-I	TC			$50	$49	$46	$46	$45	$45	$44	$44	$43
OHC-V	TC			$100	$98	$93	$92	$90	$89	$88	$87	$86
OHV-V	TC			$50	$49	$46	$46	$45	$45	$44	$44	$43

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.5 Dual Cam Phasing (DCP)

Based on the analysis for the Draft TAR, EPA estimated the effectiveness of DCP to be between 4.1 to 5.5 percent.

In comments on the Draft TAR, Toyota suggested that EPA's estimate of DCP effectiveness was too high "to account for DCP effectiveness differences resulting from the combination of engine displacement, R/L, TIM, and open duration setting of intake air camshaft. Similar to the comment on intake cam phasing cited above, the comment did not share specific data on engines, specific camshaft phasing hardware and resultant effectiveness relative to hardware used, making it difficult to further assess the claim. EPA notes that the effectiveness data used in the Draft TAR is consistent with published and peer-reviewed data cited in the FRM, the Draft TAR and this Proposed Determination, and reflects performance consistent with the range of authority for ICP and DCP hardware for which cost estimates were developed. EPA therefore believes that the effectiveness estimate used in the Draft TAR remains applicable for this Proposed Determination.

The costs associated with dual cam phasing are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.64 Costs for Dual Cam Phasing (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$77	24	$73	$72	$71	$69	$68	$67	$66	$65	$65
OHC-V	DMC	$164	24	$157	$154	$151	$149	$146	$144	$142	$140	$139
OHC-I	IC	Med2	2018	$30	$29	$22	$22	$22	$22	$22	$22	$22
OHC-V	IC	Med2	2018	$63	$63	$47	$47	$47	$47	$47	$47	$47
OHC-I	TC			$103	$101	$93	$91	$90	$89	$88	$87	$86
OHC-V	TC			$221	$217	$199	$196	$194	$191	$189	$187	$186

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.6 *Discrete Variable Valve Lift (DVVL)*

Based on the analysis for the Draft TAR, EPA estimated the effectiveness for DVVL at 4.1 to 5.6 percent.

In comments on the Draft TAR, Toyota suggested that EPA's estimate of DVVL effectiveness was too high because "DVVL effectiveness differs from combination of engine displacement, road load (R/L), T/M, and open duration setting of intake air camshaft." Similar to the comments on intake cam phasing and dual cam phasing cited above, the comment did not share specific data on engines, specific camshaft phasing hardware and resultant effectiveness relative to hardware used, making it difficult to further assess the claim. EPA notes that the effectiveness data used in the Draft TAR is consistent with published and peer-reviewed data cited in the FRM, the Draft TAR and this Proposed Determination, and reflects performance consistent with DVVL hardware for which cost estimates were developed. EPA therefore believes that the effectiveness estimate used in the Draft TAR remains applicable for this Proposed Determination.

The costs associated with discrete variable valve lift are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.65 Costs for Discrete Variable Valve Lift (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$131	24	$125	$123	$121	$119	$117	$115	$113	$112	$111
OHC-V	DMC	$190	24	$182	$178	$175	$172	$169	$167	$165	$162	$160
OHV-V	DMC	$271	24	$260	$255	$250	$246	$242	$238	$235	$232	$229
OHC-I	IC	Med2	2018	$50	$50	$38	$38	$38	$37	$37	$37	$37
OHC-V	IC	Med2	2018	$73	$73	$55	$54	$54	$54	$54	$54	$54
OHV-V	IC	Med2	2018	$105	$104	$78	$78	$78	$78	$78	$77	$77
OHC-I	TC			$176	$173	$158	$156	$154	$153	$151	$149	$148
OHC-V	TC			$255	$251	$230	$227	$224	$221	$219	$217	$214
OHV-V	TC			$364	$359	$328	$324	$320	$316	$313	$309	$306

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.7 *Continuously Variable Valve Lift (CVVL)*

Based on the analysis for the Draft TAR, EPA estimated the effectiveness for CVVL at 5.1 to 7.0 percent.

In comments on the Draft TAR, Toyota suggested that EPA's estimate of CVVL effectiveness was too high, citing "the same reasons cited above" with regard to ICP, DCP, and DVVL. Other than making a general statement, the comment did not share specific data on engines, specific hardware and resultant effectiveness relative to hardware used, making it difficult to further assess the claim. EPA notes that the effectiveness data used in the Draft TAR is consistent with published and peer-reviewed data cited in the FRM, the Draft TAR and this Proposed Determination, and reflects performance consistent with CVVL hardware for which cost estimates were developed. EPA therefore believes that the effectiveness estimate used in the Draft TAR remains applicable for this Proposed Determination.

The costs associated with continuously variable valve lift are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.66 Costs for Continuously Variable Valve Lift (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OHC-I	DMC	$197	24	$188	$184	$181	$178	$175	$173	$170	$168	$166
OHC-V	DMC	$360	24	$345	$338	$332	$326	$321	$316	$312	$308	$304
OHV-V	DMC	$393	24	$376	$369	$362	$356	$350	$345	$340	$336	$332
OHC-I	IC	Med2	2018	$76	$76	$56	$56	$56	$56	$56	$56	$56
OHC-V	IC	Med2	2018	$139	$139	$104	$103	$103	$103	$103	$103	$103
OHV-V	IC	Med2	2018	$151	$151	$113	$113	$113	$112	$112	$112	$112
OHC-I	TC			$264	$260	$237	$234	$231	$229	$226	$224	$222
OHC-V	TC			$484	$477	$435	$430	$424	$419	$415	$411	$407
OHV-V	TC			$527	$520	$475	$469	$463	$458	$453	$448	$444

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.1.8 Atkinson Cycle Engines in Non-HEV Applications

In the last few years, a new generation of naturally aspirated SI Atkinson Cycle engines applicable outside of HEVs have been introduced into light-duty vehicle applications. The most prominent application of this technology is the Mazda SKYACTIV-G system. It combines direct injection, an ability to operate over an Atkinson Cycle with increased expansion ratio, wide-authority intake camshaft timing, and an optimized combustion process. This type of engine operation is not limited to naturally aspirated engines and when applied to boosted engines is referred to as "Miller Cycle," as described below.

2.3.4.1.8.1 Effectiveness Data Used and Basis for Assumptions

EPA initiated an internal study to investigate potential improvements in the incremental effectiveness of Atkinson Cycle engines through the application of cooled EGR, an increase in compression ratio, and 2/4 cylinder deactivation. Cooled EGR offered the potential for additional knock mitigation, increased compression ratio, and reduced pumping losses. The use of cylinder deactivation held potential for additional pumping loss reduction under light-load conditions. Initially, EPA studied the potential for improvements using 1-D gas dynamics/0-D combustion simulation software.[FFF] A 2.0L Mazda SKYACTIV-G GDI Atkinson Cycle engine was thoroughly benchmarked by EPA with the engine dynamometer test facilities at the EPA-NVFEL laboratory in Ann Arbor, MI. Performance data and physical dimensions for the engine and its gas exchange and combustion processes were used by EPA to build and validate the simulation. Details of the study, including methods used to build the engine model, model validation, and initial engine modeling results are provided in Lee et al. 2016.[554] A comparison of engine dynamometer test data to modeling results for a 1-point increase in geometric CR and

[FFF] Gamma Technologies "GT-POWER."

the use of cEGR with an Atkinson Cycle engine are shown in Figure 2.102. Single point values for regions of operation important for the regulatory drive cycles are shown from approximately 2-bar BMEP to 7 or 8 bar BMEP and from 1500 rpm to 2500 rpm (i.e., comparable to areas of high frequency of operation over the UDDS and HWFET as shown in Figure 2.80). Engine simulation results showed the potential for an approximately 3 percent to 9 percent incremental effectiveness in areas of operation of importance for the FTP and HWFET regulatory cycles using a combination of cooled EGR and a 1-point increase in compression ratio (14:1), with the largest improvements (6 to 9 percent incremental) occurring between 4-bar and 8-bar BMEP. While the increased expansion from a 1-point increase in geometric compression ratio incrementally improves cycle efficiency, most of the improvement in effectiveness was due to reductions in pumping losses from cooled cEGR.

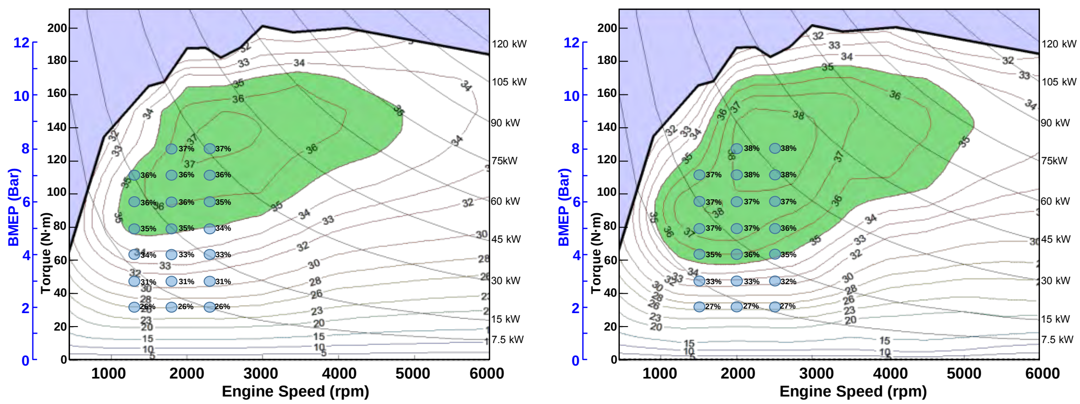


Figure 2.102 Comparison of a 2.0L Mazda SKYACTIV-G engine with a 13:1 geometric compression ratio to engine simulation results of a comparable engine with a 1-point increase in geometric compression ratio (14:1) and cooled, low-pressure EGR.[GGG]

Simulation results also show potential for an approximately 3 percent to 12 percent incremental effectiveness in areas of engine operation with significant importance for the UDDS and HWFET drive cycles using a combination of cooled EGR, a 1-point increase in compression ratio (14:1), and with fixed (2-cylinder) cylinder deactivation when operating below 5-bar BMEP and for engine speeds of 1000 rpm to 3000 rpm, and depending on how much cylinder deactivation can be active within this range of operation. Simulation results also show an incremental effectiveness of approximately 3 percent to 7 percent (Figure 2.103) when comparing the cooled EGR/higher geometric compression ratio results with and without cylinder deactivation. This is consistent with other published results for both production and proof-of-concept fixed (not dynamic) cylinder deactivation.[559,560,565] This represents a maximum potential for fixed cylinder deactivation within the speed and load range analyzed. Based on benchmarking results of the GM "Ecotec3" 4.3L V6 engine, we estimated that cylinder deactivation would available approximately 60 percent of the time within this speed and load range for the analysis within the draft TAR and the Proposed Determination. This is a

[GGG] The simulation results presented in Figure 2.102 and Figure 2.103 include kinetic knock modeling and calibration of the simulation to knock induction comparable to the original engine configuration for both Tier 2 certification test fuel (E0, 96 RON) and LEV III certification test fuel (E10, 88 AKI, 91 RON). An adequate representation of knock-limited torque within an engine simulation requires careful experimental validation of the kinetic knock model used by the simulation.

conservative estimate that does not take into use of improved crankshaft dampening systems or other NVH measures that would reasonably be expected to extend the amount of cylinder deactivation operation possible within this region of engine speed and BMEP.[566]

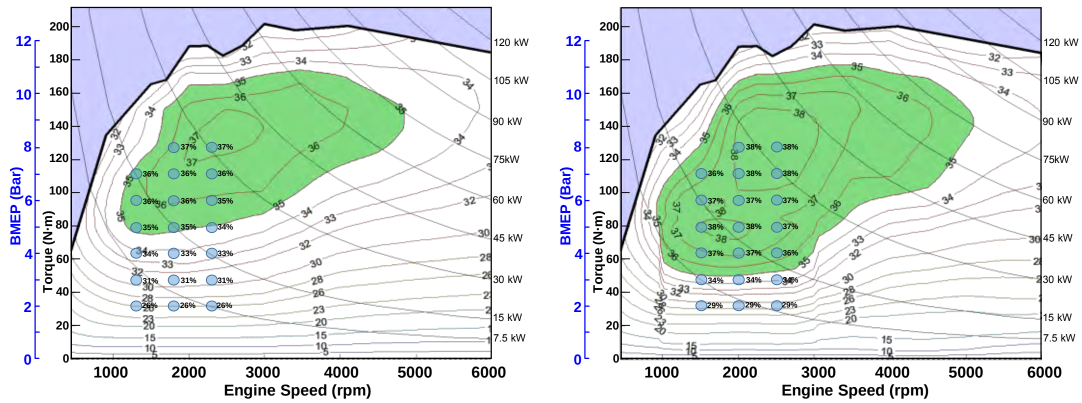


Figure 2.103 Comparison of a 2.0L Mazda SKYACTIV-G engine with a 13:1 geometric compression ratio to engine simulation results of a comparable engine with a 1-point increase in geometric compression ratio (14:1), cooled, low-pressure EGR and cylinder deactivation with operation on 2 cylinders at below 5-bar BMEP and 1000 - 3000 rpm.

The EPA internal study on Atkinson Cycle engines entered a second phase involving engine dynamometer validation of the simulation results using a EU-market version of the Mazda SKYACTIV-G engine with increased geometric compression ratio (14:1), a proof-of concept low-pressure-loop cooled EGR system, and the use of a dual-coil offset (DCO) ignition system to improve EGR tolerance of the engine (see Figure 2.104).[567,568] Initial results have been promising. The improved ignition characteristics of the DCO ignition system has allowed an increase in the range of part-load engine operation at relatively high rates (approximately 20 percent) of cooled EGR beyond that of the relatively conservative, fixed EGR map used in the simulation study. This allowed further reductions in part-load pumping losses which improve fuel efficiency while maintaining a COV of IMEP[HHH] of less than 3-4 percent, which is comparable to that of the original engine configuration.

[HHH] Coefficient of variation (COV) of indicated mean effective pressure based on high-speed in-cylinder pressure measurements. This is a commonly used indicator of combustion instability and would typically be kept to values that are under 3% to 5% depending on operating conditions and engine application. Lower COV corresponds to smoother engine operation.

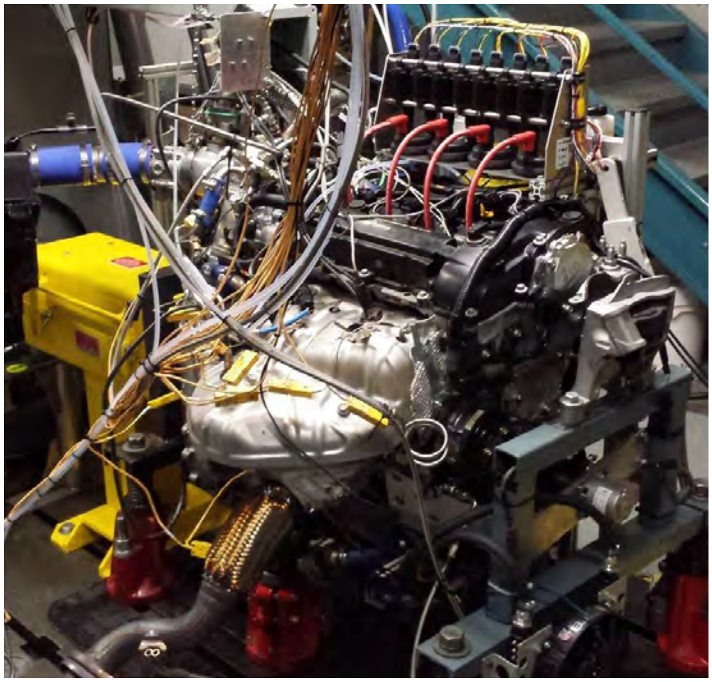


Figure 2.104 Mazda 2.0L SKYACTIV-G engine with 14:1 geometric compression ratio, cooled low-pressure external EGR system, DCO ignition system, and developmental engine management system undergoing engine dynamometer testing at the U.S. EPA-NVFEL facility in Ann Arbor, MI.

The ignition system improvements also allowed further optimization internal EGR (iEGR) and external cEGR rates and allowed higher EGR rates to be shifted to and broadened to cover more operation over the UDDS and HWFET (see

Figure 2.105). The calibrated rates of cEGR arrived at during engine dynamometer testing were remarkably similar to published data for a production application of cEGR to an Atkinson Cycle engine.[571]

The CO_2 reductions achieved during engine dynamometer testing occurred over a broader area of operation than for the engine simulation conducted for the draft TAR. At engine speeds below 2000 rpm, larger reductions in CO_2 were achieved during engine testing between 4 and 8 bar BMEP although simulations results showed larger CO_2 reductions below 2.5 bar BMEP. At all other conditions above 2000 rpm and 1 bar BMEP, engine test results achieved comparable or larger reductions in CO_2 emissions than the engine simulation results from the draft TAR. See Figure 2.106 for a graph of modeled and tested CO_2 effectiveness. Note that the regions of CO_2 effectiveness roughly correlate with the EGR rates shown in Figure 2.105.

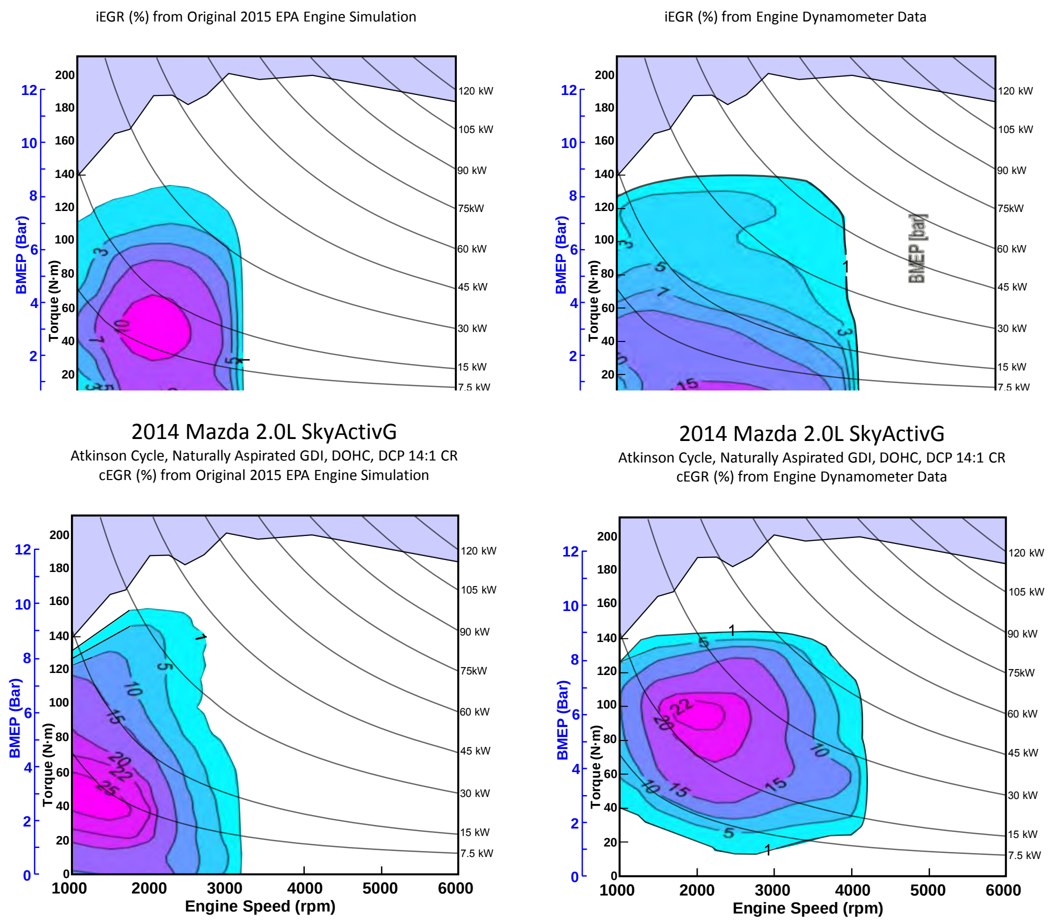


Figure 2.105 Modeled internal EGR and cEGR rates (in percent) from the draft TAR engine simulation (left top and left bottom, respectively) compared to internal EGR and cEGR rates achieved during engine testing (right top and right bottom, respectively).

Note: White areas of the contour plots reflect <1% (effectively zero) EGR.

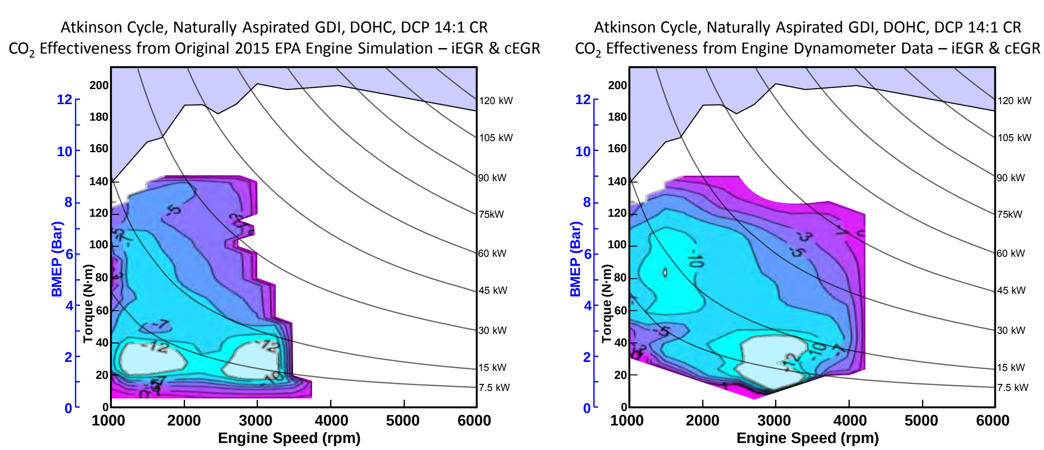


Figure 2.106 Modeled CO_2 effectiveness for internal and cEGR from the draft TAR engine simulation (left) compared to CO_2 effectiveness achieved during engine testing (right).

The updated laboratory engine test data and simulations of ATK2 using cEGR described above were very encouraging and suggest that the Draft TAR effectiveness projections are conservative. Therefore, it was decided that the internal and cEGR rates and resulting fuel maps and CO2 effectiveness from the engine simulations used in the Draft TAR were still appropriate to use for the Proposed Determination analysis. Consequently, the higher CO2 effectiveness achieved during additional laboratory engine testing was not reflected within LPM CO2 effectiveness for the Proposed Determination. In summary, the CO2 effectiveness used within the Proposed Determination for the application of cEGR to non-HEV Atkinson Cycle engines has been confirmed with laboratory testing and is expected to be conservative relative to the effectiveness that was achieved during engine dynamometer testing.

Furthermore, in the absence of engine dynamometer validation of the kinetic knock model, engine displacements were increased by 5 percent for all "advanced" ATK2 engine packages to which a 1-point increase in geometric CR and cEGR are applied. This was done to reflect a reduction in peak BMEP and a resultant necessity for increased engine displacement to maintain vehicle acceleration performance. This adjustment resulted in a decrease in LPM CO_2 effectiveness for the proposed determination relative to the Draft TAR of approximately 0.1 to 0.65%, with the range roughly coinciding with low and high power-to-weight-ratio vehicles, respectively.

Cylinder deactivation (DEAC) was also simulated during engine dynamometer testing by disabling valve events to two cylinders via cam-follower removal and allowing trapped air to act as an "air-spring" within the two disabled cylinders. Figure 2.107 shows the CO_2 effectiveness when combining operation on 2-cylinders at below 3.75-bar BMEP[III] and between 1000 and 3000 rpm with cEGR and with internal EGR optimized for two-cylinder operation. It should be noted that the effectiveness due to simulated cylinder deactivation shown in Figure 2.107 should be considered a "maximum" effectiveness within the speed and load range that cylinder deactivation was simulated during dynamometer testing.

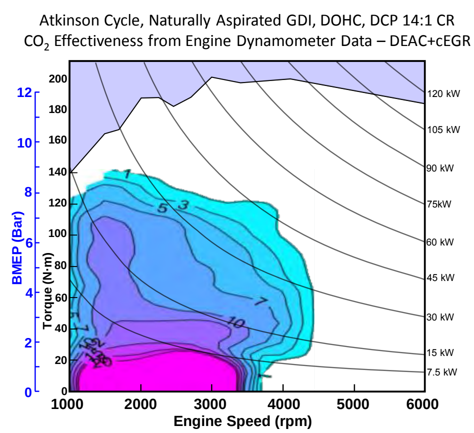


Figure 2.107 CO_2 effectiveness achieved during engine testing with cEGR and simulated 2-cylinder fixed cylinder deactivation from 1000 to 3000 RPM and at less than 3.75 BMEP.

[III] BMEP is reported relative to the entire engine displacement with both active and inactive cylinders.

The effectiveness achieved from simulated cylinder deactivation during testing of modified Mazda SKYACTIV-G engine was also very similar to effectiveness results presented by Mazda for their developmental cylinder deactivation system for the 2.0L SKYACTIV-G, although the Mazda system appears to use a broader engine speed window than what was considered during simulation for the Draft TAR or subsequent engine dynamometer validation.[561]

Cylinder deactivation along with both internal and cEGR rates and resulting fuel maps and CO_2 effectiveness from the engine simulations developed for the draft TAR were also used for Proposed Determination and thus the higher CO_2 effectiveness achieved during engine testing of an Atkinson Cycle engine with simulated cylinder deactivation was not reflected within LPM CO_2 effectiveness for the Proposed Determination. The CO_2 effectiveness used within the Proposed Determination for the application of cEGR to non-HEV Atkinson Cycle engines is thus expected to be somewhat conservative relative to the effectiveness that was achieved during engine dynamometer testing or relative to other similar work demonstrated by Mazda.[561]

The Alliance of Automobile Manufacturers (AAM) and FCA commented that EPA's results used optimistic ATK2 engine fuel consumption maps. However, they did not provide data or other information to substantiate its claim that EPA's engine dynamometer fuel consumption measurements using a MY2014 Mazda OEM production 2.0L SKYACTIV-G, upon which the ATK2 packages from the TAR analysis are based, were in any way unrepresentative of this engine's actual performance. AAM did provide a fuel consumption "difference map" (see chart B-1 from the AAM public comments which is reproduced in Figure 2.108) purporting to show the difference between a map developed from EPA-published test data using Tier 2 certification gasoline and data provided to AAM by USCAR using an unspecified 91 RON fuel. AAM implied that there were areas of concern that call into question the ATK2 fuel maps as a baseline for further theoretical additions of technology. This AAM map is referred to as the "difference map" in the following response.

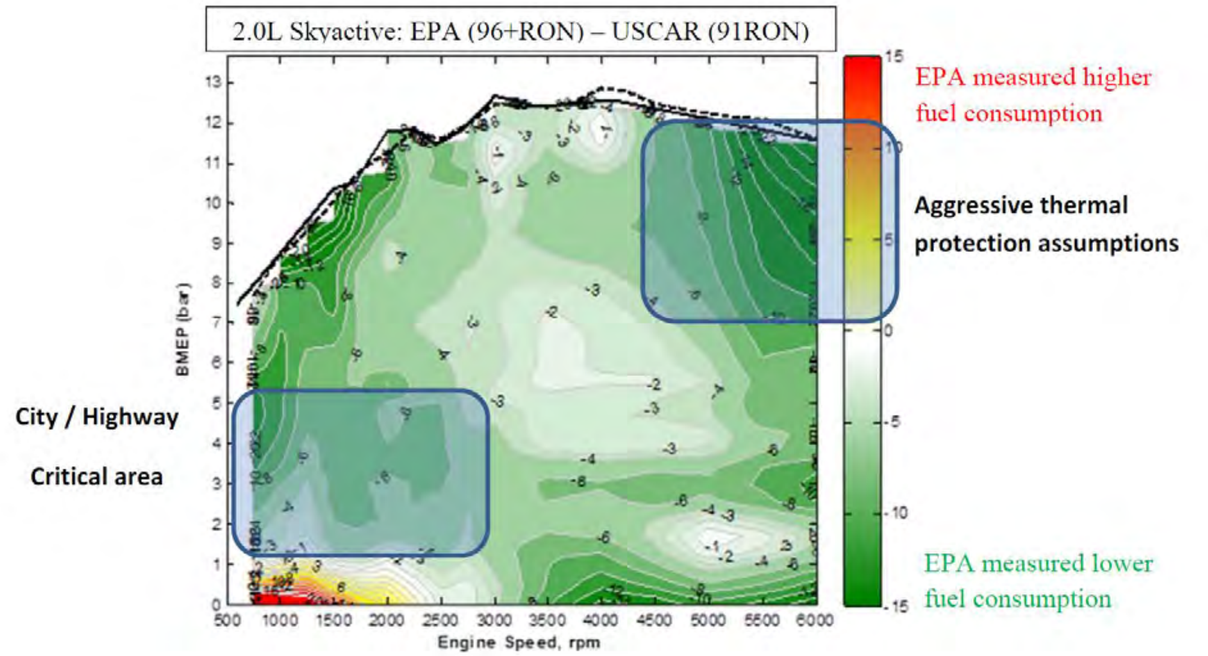


Figure 2.108 "Difference map" comparison provided by AAM between EPA data generated using Tier 2 certification gasoline and "USCAR 91 RON data" for a Mazda SKYACTIV-G 2.0L engine. (AAM Fig B-1)[JJJ]

First, from a regulatory compliance standpoint, AAM's comparison between Tier 2 and other fuels has no basis. This is because the stringency of the GHG (and fuel economy) standards is based exclusively on use of Tier 2 fuel. Furthermore, EPA has investigated the difference in CO2 performance between Tier 2 and Tier 3 test fuels, and preliminary data indicate that vehicles actually perform slightly better from a CO2 standpoint (i.e. emit less CO2) using Tier 3 fuel. This is because Tier 3 test fuel has less energy content but also a lower carbon content than Tier 2 fuel. EPA has already indicated in the Tier 3 rule package that, as a convenience to avoid testing using different fuels, EPA will make an adjustment to convert CO2 results using Tier 3 test fuel to account for the different fuel properties. Please see Chapter 2.3.1.3 (Fuels) for additional discussion.

In any case, the AAM commenter provided virtually no information regarding test and or analytical methods, assumptions, fuel properties, environment test conditions, how the engine was controlled or how control was modeled, among other pertinent factors. Thus, AAM did not provide any fuel specifications other than RON, so it is unclear if the map purports to show a difference due to RON or a difference due to a combination of factors that also impact fuel consumption (e.g., differences in fuel ethanol content and/or net energy content or other fuel properties). Use of any future certification fuels with differing properties would also necessarily include a correction back to GHG performance on Tier 2 certification fuel, as EPA has already indicated for Tier 3 test fuel, again as noted above.

Although the "difference map" provided by AAM is identified as showing fuel consumption differences, no specific units were identified by AAM, so it is not clear if the map shows

[JJJ] Alliance of Automobile Manufacturers Comments on Draft Technical Assessment Report. EPA docket number EPA-HQ-OAR-2015-0827-4089-A1.

absolute differences in fuel mass flow rate, absolute differences in fuel volumetric flow rate, or percentage differences on either a mass or a volumetric basis. AAM identified USCAR as the source of data used for the comparison, but it is unclear if the data compared to EPA's measured fuel consumption was generated using modeling, if it was generated using data from engine dynamometer testing, or if it was estimated by some other means.

Neither the underlying test conditions nor the experimental design were shared for any data that may have been generated, so it is impossible to even assess the validity or veracity of the data presented. The absence of underlying data or other supporting details in the comment makes these issues a matter of conjecture. For example:

- If the data used to calculate the fuel consumption difference map was generated from USCAR engine dynamometer testing, it is unclear why AAM/USCAR would only test an engine using a 91 RON fuel and then compare the results to EPA data. Such a comparison inherently introduces different uncertainty by comparing data from different engines tested in different laboratories, potentially under different testing and operating conditions.
- AAM did not share the test conditions under which the engine was tested, any procedures used to ensure data quality, any measured analytical fuel properties other than RON, the number of data points used to generate the fuel consumption "difference map", or the interpolation method used to generate the "difference map".
- A more reasoned difference map comparison would be to conduct independent testing with both a Tier 2 certification fuel and a 91 RON, or Tier 3 certification, fuel using the same engine in order to generate a "difference map" with commonality of engine, engine management system calibration, experimental equipment, and laboratory equipment calibration.
- A more valid difference map comparison would also involve an engine from the same vehicle application to demonstrate any fuel consumption differences without the added uncertainty of lab-to-lab and design-of-experiment differences.

In summary, the commenter provided no information to compare vintage or application of the actual engine or engines tested, and did not state whether or not testing was conducted. More specifically, the comments did not state: test and or analytical methods, assumptions, fuel properties, environment test conditions, how the engine was controlled or how control was modeled, the number of data points gathered to generate the AAM "difference map" to assure that identical testing and a sufficient fit of data was performed. For example, not enough information was provided to know how accessory loads or engine cooling were handled in any testing that may have been performed.

While AAM shared neither the underlying data, underlying assumptions, nor even the units used within the "difference map" with EPA, we nevertheless independently generated a complete set of "difference maps". As part of ongoing engine technology benchmarking activities, EPA tested a MY2014 Mazda SKYACTIV-G 2.0L engine with a geometric compression ratio of 13:1 (i.e. ATK2) using fuels having different properties, including differences in RON. Our comparison of the engine operation on a brake-thermal-efficiency basis, or after correction of percentage mass differences in fuel consumption to an equivalent energy basis, revealed little or no discernable difference between fuels over the areas of concern for regulatory testing beyond the differences in energy content between the fuels. The results of EPA's engine map comparisons is available in Appendix D.

In their comments, AAM and FCA expressed concerns about the practical limitations for cEGR to limit engine knock. EPA conservatively considered practical limitations of cEGR to limit engine knock and took these limitations into account when modeling the impacts of cEGR on engine operation. In EPA's assessment of cEGR effectiveness, EPA not only took into consideration the practical limitations for improving knock-limited spark advance (KLSA), but also practical limitations in applying cEGR to reduce pumping losses at part-load conditions.

Part-load pumping loss reductions from cEGR are more important to the drive-cycle effectiveness of cEGR than use of cEGR solely for knock abatement. Typically, improvements to KLSA would not significantly impact performance on the FTP or HWFET drive cycles since knock-limited operation is either not encountered or not often encountered over these cycles with naturally aspirated engines, including those using Atkinson Cycle. Non-HEV Atkinson Cycle engine applications reduce effective compression ratio under part-load conditions to reduce pumping losses from throttling. Thus, limits on part-load cEGR application due to combustion stability result in more important impacts on cEGR effectiveness under the conditions encountered over the regulatory drive cycles used for GHG compliance (e.g., sub-6 bar BMEP for engines like the Mazda SKYACTIV-G) than would be the case of using cEGR solely for improving knock-limited spark advance.

The cEGR limits investigated by EPA included investigating adverse effects on combustion phasing and the potential for deterioration of combustion stability at part load, which potentially limit the availability of pumping loss reductions from EGR over the regulatory drive cycles. The 0-D/1-D models used for investigation of cEGR effectiveness could not adequately account for changes to COV of IMEP (an important indicator of combustion stability), so limits on cEGR based upon published literature were initially investigated by EPA during modeling.

During engine dynamometer testing to validate the modeling results, EPA made improvements to the ignition system to allow the use of higher cEGR rates at some part-load conditions representing important areas of operation for the regulatory drive cycles. This allowed engine operation at higher cEGR rates than were considered during modeling while still achieving comparable or improved COV of IMEP when compared to the OE engine configuration with lower geometric compression ratio and no external EGR.

Figure 2.105 compares modeled internal EGR and cEGR rates with those actually achieved during engine testing with a developmental cEGR system, 14:1 geometric compression ratio, and revised valve event timing. The results used in the Draft TAR and the Proposed Determination analyses continue to reflect the use of a more conservative cEGR strategy, with somewhat reduced cEGR rates relative to what has been demonstrated by EPA during engine dynamometer developmental testing.

The application of cEGR technology is found in many light-duty vehicles in the current fleet. As such, the feasibility of applying cEGR to mitigate knock and reduce part-load pumping losses has already been established. Although cEGR development has been a significant topic of auto manufacturer research and development in recent years for both naturally aspirated and turbocharged applications, AAM shared no data with EPA showing achievable cEGR rates and cEGR operational limitations from engine simulation, engine dynamometer developmental testing, or from actual production applications of cEGR that have been introduced in the U.S., Europe and Asia.[569,570,571,572,573]

Further comments from AAM and Ford expressed concern that EPA did not take into account the impact of 91 RON market and certification test fuels when developing fuel economy effectiveness. While EPA's analysis of effectiveness of gasoline fueled engines did not include analysis of effectiveness using Tier 3 certification gasoline (E10, 87 AKI), protection for operation in-use on 87 AKI E10 gasoline was included in the analysis of engine technologies considered both within the Draft TAR and this Proposed Determination.

As noted in the discussion on Atkinson cycle engines in Chapter 2.3.4.1.8, from the current regulatory compliance standpoint, determining fuel economy effectiveness using any fuel other than Tier 2 fuel has no basis. Consistent with Federal regulations under the Clean Air Act and EPCA, when test fuel properties are updated EPA will determine appropriate test procedure adjustments in order maintain the same level of stringency of the GHG standards should manufacturers elect to test vehicles using Tier 3 certification fuel (as noted in that earlier response, EPA is providing this accommodation to ease testing burden, although the GHG rules specify Tier 2 fuel as the test fuel). A correction factor for application to future vehicles certified to the GHG standards using Tier 3 gasoline that will allow correction of CO2 emissions in a manner that accounts for differences between Tier 2 and Tier 3 certification fuels is currently under regulatory development with manufacturers, industry, and other stakeholder involvement. Please refer to Chapter 2.3.1.3 (Fuels) for further discussion.

In other comments, AAM and FCA expressed concern that the benefits modeled by GT-POWER for the Advanced Atkinson Tech Package have not been verified by manufacturers or by the agencies. EPA notes that CAE models, such as GT-POWER, are routinely used by manufacturers to aid in the development of engine and other technologies to comply with EPA standards. Furthermore, estimated effectiveness from CAE modeling is conservative relative to data generated via engine dynamometer validation (see 2.3.4.1.8.1). The AAM commenters are correct in stating that models, including 0D/1D combustion and flow models like GT-POWER, need careful validation relative to engine dynamometer performance in order to be used as predictive tools, and EPA has conducted hardware validation as described below and in section 2.3.4.1.8.1.

AAM's comment referred to SAE Paper 2016-01-0565, which documents part of the validation process, including validation that the model can predict operational characteristics of a base engine design. AAM unfortunately significantly misquoted a sentence from this paper: "[the] BSFC map [of the ATK2 engine] at 14:1 CR [with cooled EGR and cylinder deactivation] could not be validated with engine dynamometer operation, even with use of 96 RON E0 fuel, due to the onset of knock." The parentheticals added by AAM are both wrong and misleading. First, the BSFC map at 14:1 geometric compression ratio does not represent either ATK2 or testing of an engine with cooled EGR and/or cylinder deactivation.

ATK2 effectiveness was developed by EPA via benchmarking of a production, unmodified MY2014 U.S.-market Mazda SKYACTIV-G 2.0L 4-cylinder Atkinson Cycle engine with a 13:1 geometric compression ratio. The engine with the 14:1 geometric compression ratio originally discussed in the SAE paper was a European-market version of the engine not available in the U.S. and with hardware and EMS calibration developed for operation on higher octane, predominantly E0 fuels available in Europe. An unmodified European version of this engine without cEGR and without other significant hardware and calibration changes could not reasonably be expected to have capability to operate on U.S. fuels, even premium-grade fuels, without a risk of knock onset.

At the time that SAE Paper 2016-01-0565 was prepared by EPA staff, developmental hardware that could potentially enable the use of the higher geometric compression ratio hardware, such as cEGR, a developmental/open EMS allowing engine calibration, higher energy ignition system, and possibly cooling system improvements was not yet available and thus the entire point of using CAE tools was to allow EPA to investigate potential improvements as future technologies were applied to the engine using reasonable engineering assumptions. This is a long-recognized way of assessing and reasonably predicting technology effectiveness. See, e.g. *Amer. Petroleum Inst. v. EPA, 706 F. 3d 474,, 480 (D.C. Cir. 2013).*

EPA has completed initial hardware validation of the GT-POWER modeling of non-HEV Atkinson Cycle engine simulations conducted for the Draft TAR. While EPA continued its hardware validation and incremental improvement of GT-POWER modeling of this specific application of technologies, EPA engineering staff shared its initial results used in the Draft TAR regarding cEGR and CDA GT-POWER model validation at the higher geometric compression ratio with engineering staff from AAM member companies at an April 12, 2016 USCAR meeting. At that meeting, EPA staff responded informally to questions and participated in a discussion of both Atkinson Cycle engine technology and the use of external cEGR and CDA with Atkinson Cycle engines. EPA staff also used design of experiments for both GT-POWER modeling and for hardware validation of the technologies assessed using GT-POWER modeling. During the course of the meeting, no indication was made that the use CAE tools such as GT-POWER modeling were inappropriate or “not accurate enough for reference” in the MTE. Such tools are regularly used by the automotive industry themselves to guide product development and are used extensively by USCAR to guide research and development to improve internal combustion engine and vehicle efficiency, hence the interest in inviting EPA staff make a presentation at the meeting. EPA received no formal "meeting minutes", as referenced by AAM, from either AAM or from USCAR. EPA's presentation materials from the USCAR meeting are available in the Docket.[574]

The hardware development, engine dynamometer testing, model validation and updating of the GT-POWER model do represent significant further study and development of these technologies. EPA has completed much of this work, which as explained earlier, confirms that our estimates for the Proposed Determination are appropriate. Initial test results of engine dynamometer testing with cEGR, 14:1 geometric CR and CDA are summarized in Chapter 2.3.4.1.8 and are the topic of upcoming journal and technical paper submissions. These initial hardware validation results indicate that the modeling approach used within GT-POWER was conservative with respect to the determining the effectiveness of future technologies applied to ATK2.

AAM also made other erroneous assertions related to SAE Paper 2016-01-0565 and the April 12, 2016 USCAR meeting. For example, AAM claimed that there was a "serious clerical error in translating the GT-POWER full load torque data to ALPHA which was then carried into the LPM’s calibration" and that "in the SAE paper 2016-01-0565 the GT-POWER model correctly limited the full load torque of the engine due to knock onset" (p. 49 AAM comments). This statement is incorrect. EPA notes that work to develop a model of knock limited peak torque had not been completed in time for the initial SAE 2016-01-0565 paper, and no such data or modeling was referenced as part of that work. Furthermore, the torque curve claimed by AAM to be from EPA's SAE paper does not match either torque limits or data plotting limits used anywhere within SAE 2016-01-0565. Figure 2.109 shows the discrepancy alleged by AAM in figure B-2 of their comments.

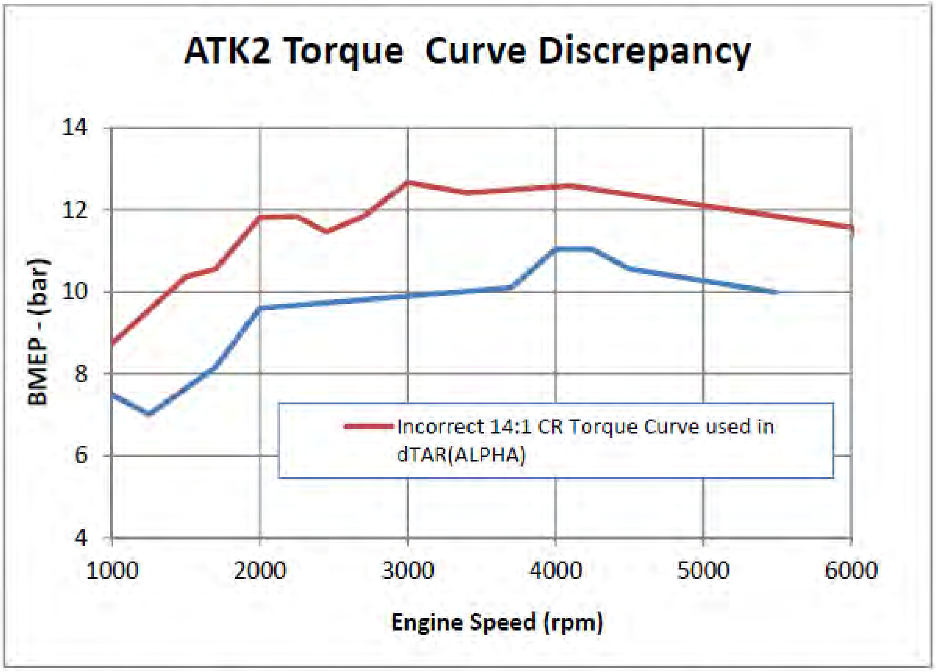


Figure 2.109 This figure was reproduced from "Figure B-2" of the AAM comments purporting to show a discrepancy between the torque curves used in SAE 2016-01-0565 vs. those used within the ALPHA model.

Figure 2.110 overlays EPA data onto the original AAM figure showing the following additional torque data:

- Maximum plotted torque (not peak torque) from GT Power model of 2014 SKYACTIV-G 2.0L BSFC from SAE 2016-01-0565 (solid, orange line). Note that the limits were solely limits of the data points analyzed within GT-POWER, not knock-limited torque
- Maximum plotted torque for modeling knock induction at 13:1, 14:1, and 14:1 w/cEGR from SAE 2016-01-0565 (dashed, light blue line). Note that the limits were solely limits of the data points analyzed within GT-POWER, not knock-limited torque
- Torque curve from initial engine dynamometer testing shown in SAE 2016-01-0565 (solid green line). This torque curve represented test data from engine dynamometer benchmarking of a U.S.-market MY2012 Mazda SKYACTIV-G engine. The torque limits served as the initial developmental limits for GT-POWER model development, assessment of future technologies, and initial cEGR hardware development that

occurred after the SAE paper was published. EPA's torque mapping procedures were updated, and this torque curve has been replaced with the one described below.

- Torque curve from Chapter 5 2014 SKYACTIV-G 2.0L engine map (dashed black line). This torque curve was developed during benchmarking of the MY2012 Mazda SKYACTIV-G engine that occurred too late for inclusion in the initial SAE paper. These torque limits serve as the current limits for GT-POWER model development, assessment of future technologies, and cEGR hardware development and also serve as the torque limits used within ALPHA modeling.

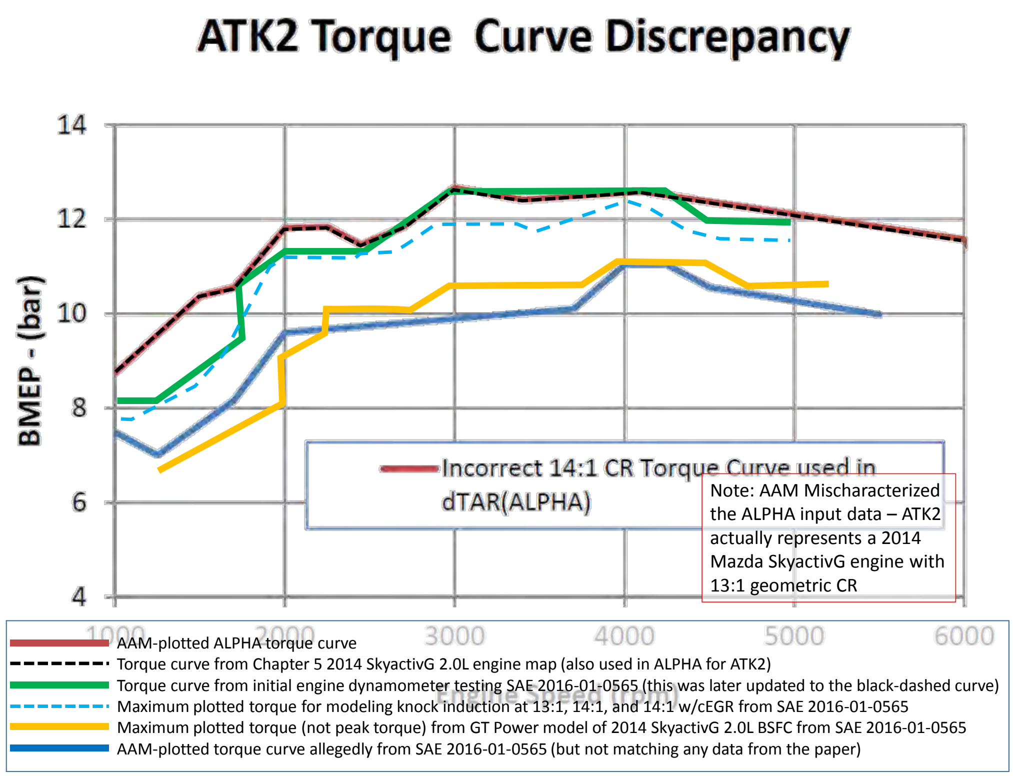


Figure 2.110 This is a reproduction of AAM figure B-2 with EPA data for two engine dynamometer derived torque curves (green and black dashed) as well the extent of modeled data points (orange, light-blue-dashed). None of the data from SAE 2016-01-0565 matches the solid blue line from the AAM comments citing SAE 2016-01-0565.

AAM's original red line approximately matches what was used by EPA within the Draft TAR and within ALPHA modeling (black dashed line) for both ATK2 (13:1 CR) and ATK2+cEGR (14:1 CR) engines. However, "ATK2" was mischaracterized in AAM's comment as representing operation of an engine using a 14:1 geometric CR. It does not. ATK2 actually uses a 13:1 geometric CR and is the same as a U.S.-market MY2014 Mazda SKYACTIV-G 2.0L engine. It is only the ATK2+cEGR that has a 14:1 geometric CR. It is not clear what AAM's solid blue line is supposed to represent because it does not represent any data presented within SAE 2016-01-0565.

The green line represents the torque limit from the first figure in the paper, converted to BMEP to be consistent with AAM's figure. It also represents what EPA was using as maximum torque/BMEP as of October 2015 and represents significantly higher torque than shown by the AAM blue line. This was later updated to the torque curve represented by the black dashed line for the TAR using data points from a later torque mapping exercise and using updated engine dynamometer mapping procedures.

The blue dashed line in the figure represents torque limits of the data plotted from the GT-POWER modeling of knock induction for the various engine configurations. EPA could have modeled the design space within GT-POWER using higher torque limits but it was not necessary in order to cover operation over the regulatory drive cycles (FTP and HWFET).

The orange line represents torque limits that EPA used for modeling BSFC in GT-POWER. Again, EPA could have modeled the design space within GT-POWER using higher torque but it was not necessary to sufficiently cover operation representative of the regulatory drive cycles.

In summary, AAM did not provide sufficient information for EPA to determine with any certainty the source of their mistaken characterization of the data from EPA's SAE paper as represented by their blue line.

EPA's SAE paper publication predated the Draft TAR release by approximately four months, but the underlying data in the SAE paper dates to October 2015 (when the paper was submitted for peer review), or approximately nine months prior to the TAR release. During those intervening months, EPA's torque mapping procedures were updated and provided slightly higher maximum torque in limited areas of operation. The more recently developed torque map is also more consistent with data presented publicly by the engine's manufacturer, Mazda, regarding the performance of the 2.0L SKYACTIV-G engine.

We also received comments that the relatively low cost of ATK2 has the impact of lowering the OMEGA-estimated cost per vehicle. In response, it is important to note that EPA's projection of ATK2 penetration in the light-duty fleet is only one of several cost-effective engine technology alternatives available to manufacturers to meet the 2025 MY GHG standards. In both the Draft TAR and this Proposed Determination, we have run sensitivities showing the impacts on costs per vehicle under a scenario where very little ATK2 technology is used for compliance. In these sensitivities, we have capped the ATK2 technology at a 10 percent level (note that Mazda uses this technology extensively today, as well as other manufacturers, and roughly 7 percent of today's fleet already uses the technology). The results show minor increases in costs per vehicle, but clearly show that pathways to compliance exist at reasonable costs and without extensive utilization of strong hybrid and electrified vehicles (see Draft TAR Table 12.48 and Section C.1.2 of the Proposed Determination Appendix).

2.3.4.1.8.2 Cost Data Used and Basis for Assumptions

Costs for this technology (future non-HEV Atkinson cycle, referred to as Atkinson-level 2 by EPA) were new to the Draft TAR as they were not part of the 2012 FRM analysis. As in the Draft TAR, we have based our Atkinson-2 technology costs on the 2015 NAS report. Table S.2 of that report shows the cost estimates presented below. Note that the NAS costs include the costs of gasoline direct injection (shown as "DI" in the NAS report row header). EPA has removed those costs (using the NAS reported values) since EPA accounts for those costs separately rather than including them in the Atkinson-2 costs. Note also that EPA always includes costs for direct injection, along with variable valve timing and other costs, when building an Atkinson-2 package.

Table 2.67 Direct Manufacturing Costs (DMC) for Atkinson-2 Technology (2010$)

Tech	Midsize Car I4 DOHC	Large Car V6 DOHC	Large Light Truck V8 OHV	Relative to
Stoichiometric Gasoline Direct Injection (NAS 2015)	$164	$246	$296	Previous tech
Compression Ratio Increase (CR~13.1, exh. Scavenging, DI (e.g. SKYACTIV-G)) (NAS 2015)	$250	$375	$500	Baseline
EPA estimate (Row 2 minus Row 1)	$86	$129	$204	Stoich GDI

Consistent with the NAS report, we have considered the NAS costs to be 2025 costs in terms of 2010$. Adjusting to 2015$, applying a learning curve (22) that bases that cost in MY2025, and applying medium 2 level complexity in calculating indirect costs results in the costs presented below for each engine type in this Proposed Determination analysis.

Table 2.68 Costs for Atkinson-2 Technology, Exclusive of Enablers such as Direct Inject and Valve Timing Technologies (dollar values in 2015$)

Engine	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I3	DMC	$93	22	$110	$108	$106	$103	$101	$99	$97	$95	$93
I4	DMC	$93	22	$110	$108	$106	$103	$101	$99	$97	$95	$93
V6	DMC	$140	22	$165	$161	$158	$155	$152	$149	$146	$143	$140
V8	DMC	$222	22	$261	$255	$250	$245	$240	$236	$231	$226	$222
I3	IC	Med2	2024	$37	$37	$37	$37	$37	$36	$36	$36	$27
I4	IC	Med2	2024	$37	$37	$37	$37	$37	$36	$36	$36	$27
V6	IC	Med2	2024	$55	$55	$55	$55	$55	$55	$55	$54	$41
V8	IC	Med2	2024	$88	$87	$87	$87	$87	$86	$86	$86	$64
I3	TC			$147	$144	$142	$140	$138	$136	$134	$132	$121
I4	TC			$147	$144	$142	$140	$138	$136	$134	$132	$121
V6	TC			$220	$217	$213	$210	$207	$204	$201	$197	$181
V8	TC			$348	$343	$337	$332	$327	$322	$317	$312	$286

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

2.3.4.1.8.3 Basis for Feasibility Assumptions

The Alliance of Automobile Manufacturers (AAM) and some of its members commented on the application of Atkinson-cycle engine technologies in the future fleet. The comments stated that EPA had been "overly optimistic" in its assessment of the technology, and that: "The advanced Atkinson technology package with CEGR and cylinder deactivation should not be utilized in the MTE analysis until the technology can be demonstrated to operate across all modeled operating points." In addition, AAM noted that the penetration rate projected by EPA for Atkinson engine technologies in 2025 MY are not feasible and may not reflect individual vehicle manufacturer's selected "technology pathway" for future compliance, suggesting that there would be insufficient lead time to implement this technology. The commenter also stated that EPA's analysis had not adequately accounted for limitations reflecting effects such as knock, cooled EGR heat rejection, and effective compression ratio.

EPA does not agree with these comments. The engine technology itself is already demonstrated in the fleet in non-hybrid applications. EPA considered two primary types of Atkinson-cycle engine technologies in the Draft TAR and we have carried these technologies into this Proposed Determination. The first Atkinson technology is referred to as "ATK1." This technology designation reflects the application of Atkinson cycle operation on engines that are primarily equipped in hybrid electric vehicles such as the Toyota Prius and the Ford Fusion. The second Atkinson technology is referred to as "ATK2." This technology designation reflects the application of Atkinson cycle engine operation in a conventional powertrain architecture, where the sole source of power to the vehicle is provided by an internal combustion engine, such as in the Mazda SKYACTIV-G architecture and the Toyota Takoma pickup truck.

In addition to the commercially available ATK2 architecture, EPA has also researched and developed further enhancements that improve the effectiveness ATK2 technology. These enhancements to ATK2 include the application of Cooled Exhaust Gas Recirculation (cEGR), Higher Compression Ratio, and cylinder deactivation (DEAC). The ATK2 technology was previously available with cEGR and a higher compression ratio in Japan and Europe and the application of DEAC on future applications of the SKYACTIV-G engine has been publicly announced by Mazda.[561,562,563,564] There are also production applications of cEGR and/or DEAC in current production Miller Cycle engines (e.g., 2016 Mazda SKYACTIV-G Turbo, VW EA211 TSI evo) which are essentially boosted versions of Atkinson Cycle. EPA has also validated modeling results of these advances using engine dynamometer testing (see 2.3.4.1.8.1)

EPA continues to believe that ATK2 engine technologies offer an additional cost effective alternative in a broad assortment of advanced gasoline engine technologies expected to be applied by vehicle manufacturers to meet future GHG standards. This group of technologies builds upon some of the foundational technology that already has wide application across the entire light-duty fleet including gasoline direct-injection (GDI), increased valve phasing authority, higher geometric compression ratios, and in some cases cooled exhaust gas recirculation (cEGR). These foundational technologies allow vehicle manufacturers to operate engines in some vehicles in both conventional and Atkinson cycle modes as demonstrated by the Chrysler Pacifica plug-in hybrid in which the 3.6L Pentastar engine is operated in Atkinson mode, and the Toyota Tacoma pick-up truck. It is also highly likely that the recently introduced updated Pentastar engine for conventional vehicles also takes advantage of its increased VVT valve phasing authority (70 degrees versus the previous 50 degrees) to expand operation in Atkinson Cycle modes. These foundational technologies allow vehicle manufacturers the ability to operate turbo-charged engines in Miller-cycle modes, which is Atkinson-cycle applied to boosted engines.

In response to comments received regarding the lead time required by manufacturers to adopt ATK2 technology, it is important to again note that EPA's projection of ATK2 penetration in the light-duty fleet is only one of several cost-effective engine technology alternatives available to manufacturers to meet the 2025 MY GHG standards. As a sensitivity analysis, this TSD presents results of an OMEGA run with penetration rates of ATK2 artificially constrained (see Section C.1.2 of the Proposed Determination Appendix). This sensitivity run still shows a cost effective pathway not requiring extensive utilization of strong hybrid and electrified vehicles remain available.

Ford and FCA both commented that some manufacturers may have already decided to go down a certain "technology pathway" that may be different from EPA's projections, and for these manufacturers the alternative technology pathway, whatever that may be, may be more cost effective than the compliance path resulting from EPA's analysis. However, for all manufacturers, EPA believes that there is sufficient lead-time to adopt the ATK2 technology. Many of the building blocks required to operate an engine in an Atkinson-mode, similar to the Mazda SKYACTIV-G engine are already available in the 2016 MY fleet. These include gasoline direct injection and a high level of control authority over the valve train.

The Mazda SKYACTIV-G engine itself was not a "clean sheet" engine design, but rather was a further development of the Mazda MZR engine family, which was introduced in 2001 as a PFI engine design with identical bore spacing and nearly identical block water jacket design. The Mazda MZR engine family was also shared with Ford Motor Company who later developed the engine into the Ford EcoBoost 2.0L engine. Finally, while the ATK2 technology was introduced into the EPA analysis in CY 2016, the technology has been in production since 2011 MY and has undergone several revisions since its initial launch. Currently Mazda, Toyota, FCA, PSA, Hyundai, and VW all have an implementation of Atkinson or Miller cycle engine operation in production in non-HEV applications, and in some cases across multiple engine families and vehicle architectures.

FCA also commented on ability to package the "4-2-1" exhaust manifold design, which provides exhaust gas scavenging in the current Mazda implementation of ATK2. FCA stated a "revamp" of a vehicle's architecture would be required to package a new exhaust manifold. While the 4-2-1 exhaust manifold is important in the Mazda current implementation of ATK2, previous implementations have used more conventional exhaust manifolds with a small (0.5 point) reduction in geometric compression ratio. More recently, Mazda has used CAE design tools to implement the 4-2-1 exhaust manifold into extremely challenging transverse-engine vehicle packages, including the Mazda2 subcompact, Mazda3 compact and Mazda CX3 small CUV.

EPA has also carefully considered whether it would be necessary to add ATK only as part of a major vehicle redesign. EPA does not believe that this is necessary. This is because the necessary foundational technologies for the ATK technology (specifically, gasoline direct-injection (GDI), increased valve phasing authority, higher compression ratios, and in some cases cooled exhaust gas recirculation (cEGR)) already are in wide application across the entire light-duty fleet.

Therefore, because ATK2 technology could build on many existing engine architectures, EPA does not believe that the implementation of the technology must be tied to major vehicle redesigns. As an example, in the case of a naturally aspirated DOHC engine with GDI and DCP, which is estimated to be approximately 45 percent of the vehicle fleet for MY2015,[575] only the following changes would necessary to fully implement Atkinson Cycle:

- High-authority (> 65 °) electric cam phasing. *Implications: Incremental cost increase, packaging improvement relative to hydraulic cam phasing (i.e., smaller), elimination of hydraulic circuit for intake cam*
- Increased intake charge motion (intake tumble). *Implications: Cylinder head casting revision with revised intake port geometry*

- Increased geometric compression ratio. *Implications: Revised piston with reduced clearance volume, revised direct injector spray targeting to match piston design*
- Improved exhaust scavenging. *Implications: Revised exhaust manifold geometry, may require some revision of belt-drive accessories and cooling fan/radiator location in some transverse applications*

In the case of any ATK2 applications that would also use cEGR, the cooling system capacity would need to be sufficient to maintain the EGR cooler temperature to just above the intake dewpoint temperature. Using the Mazda SKYACTIV-G engine as an example, the highest external cEGR rates (~22%) would typically occur at partial loads (approximate 6 bar BMEP) and relatively low engine speed (approximately 2000 rpm) (see Chapter 2.3.4.1.8, Figure 2.105), with lower external cEGR at both higher and lower engine speeds.

2.3.4.1.9 GDI, Turbocharging, Downsizing

2.3.4.1.9.1 Effectiveness Data Used and Basis for Assumptions

The TDS24 configuration used by EPA within the Draft TAR analysis was originally developed as part of engine and vehicle simulation work conducted by Ricardo, Inc. and SRA Corporation under contract with EPA, hereto referred in the Proposed Determination as the "Ricardo Study." In recent years, Ricardo has developed a number of turbocharged and downsized engine concepts with a number of characteristics in common. [576,577,578,579]

- Gasoline direct injection (GDI)
- Dual camshaft phasing and, in some cases, discrete variable valve lift
- Relatively high boost and subsequently high levels of BMEP (over 30-bar in some cases)
- Cooled, external EGR
- Advanced turbocharger boosting systems

Fuel mapping for different engine technologies was developed by Ricardo within the Study using a combination of dynamometer test results, 1D gas dynamics/0D combustion modeling, application of correction factors for displacement scaling, and use of engineering judgment. The development of fuel maps for turbocharged GDI engines within the Ricardo Study began with BSFC data obtained from Ricardo's EBDI engine development program.[576] Specifications for this engine are shown in Table 2.69 and a contour plot of BSFC versus engine speed and BMEP is also shown in Figure 2.111.

Table 2.69 Specification of Ricardo 3.2L V6 Turbocharged, GDI "EBDI" Proof-of-concept Engine.

Base Engine	Prototype V6 with IEM
Swept Volume	3190cc
Max Power @ 5,000 rpm	450 hp on E85, 400 hp on 98 RON gasoline
Max Torque @ 3,000 rpm	900 Nm on E85, 775 Nm on 98 RON gasoline
Target Max BMEP	35 bar on E85, 30 bar on Indolene (98 RON)

Compression Ratio	10.0:1
Maximum Cylinder	180 bar
Cam Phaser Authority	50° CA
Intake Boosting System	Twin, sequential turbochargers with charge air cooling after each boosting stage
Transient Torque Response Time	<1.5s to 90% SS torque at 1,500 rpm <1.0s to 90% SS torque at 2,000 rpm

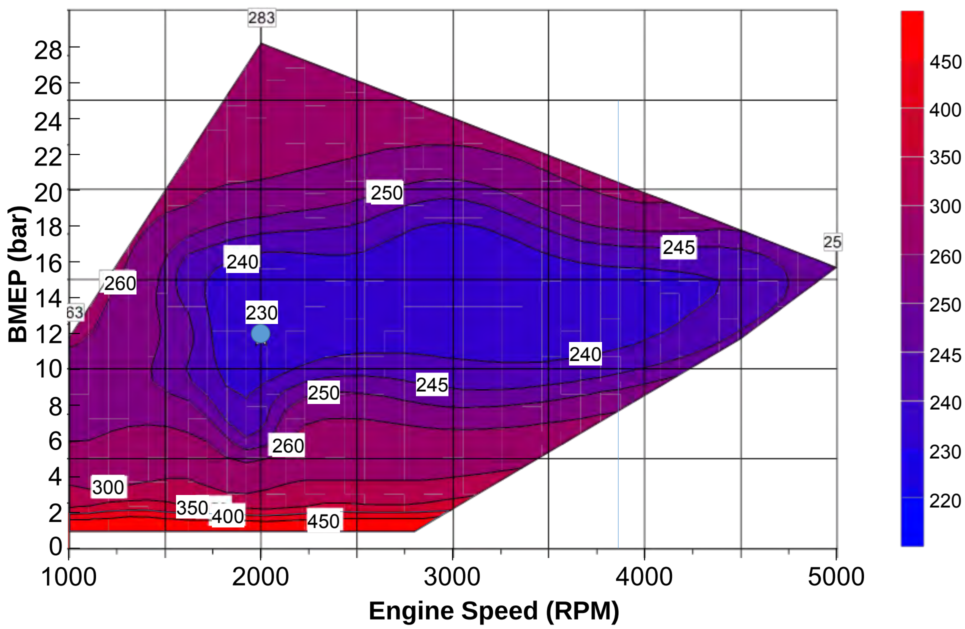


Figure 2.111 Contour plot of BSFC in g/kW-hr versus engine speed and BMEP for the Ricardo "EBDI" engine equipped with sequential turbocharging, DCP, DVVL, cEGR, IEM, and with a 10:1 compression ratio using 98 RON Indolene.

In its public comments on the Draft TAR, AAM requested that "EPA outline its rationale for using an experimental single cylinder engine map as the basis of their analysis of turbocharged downsizing technology rather than using actual production engines that were benchmarked by EPA (Ford 1.6 L EcoBoost and Ford 2.7 L EcoBoost)." The short answer is that technology has advanced past these two Ford engines, making these engines inappropriate for evaluating potential technologies for meeting the 2025 standards.

The engine EPA analyzed was a multi-cylinder engine at an advanced stage of development, as described in the papers cited within the Draft TAR and as described within Draft TAR Table 5.63, which is reproduced here in its entirety as Table 2.69. A number of technologies were used in Ricardo's development of this engine that go significantly beyond the technology of the Ford 1.6L EcoBoost (introduced in 2010) or the Ford 2.7L EcoBoost (introduced in 2015). The technologies used by Ricardo during the EBDI development program better reflect the state of technology that EPA expects to see in 2025, which is 10-15 years after the initial introduction of the engines referenced by AAM. Technologies used on the EBDI engine that are not present on the Ford EcoBoost engines referenced by AAM include:

- Variable valve lift

- External cooled EGR with both high and low-pressure loops
- Sequential turbocharging
- 50° (crank angle) of cam phaser authority
- Piezo injectors capable of multiple injections per cycle
- Higher peak cylinder pressure capability

It should also be noted that the 1.6L EcoBoost does not use an integrated exhaust manifold and the 2.7L EcoBoost does not use centrally mounted injection and, based on certification and confirmatory data, does not yet comply with Tier 3 PM emissions standards. Furthermore, the two referenced EcoBoost engines also do not reflect state-of-the-art with respect to current turbocharged/downsized engines - the VW EA211 TSI EVO, VW EA888 3B, Honda L15B7, Honda K20C, and Toyota 8AR-FTS engines all have both higher peak BTE and significantly broader regions of operation above 35 percent BTE than the engines referenced by AAM. Even in those cases, only the VW EA211 has an advanced boosting system (VNT) and cEGR, but lacks the range of cam phaser authority, VVL, peak cylinder pressure capability and more advanced injection system of Ricardo EGRB. Comparisons to three of these current production engines were presented in Chapter 5 of the TAR and are reproduced here in Figure 2.113, Figure 2.114, and Figure 2.115 and will be discussed later. It should also be noted that the multi-cylinder engine developed by Ricardo was used as part of a proof-of-concept Class 3b light-heavy-duty truck demonstration, and thus the project also included further in-chassis development.[580]

Although not captured within the EGRB map (see Figure 2.111), Cruff et al. show performance data up to 30-bar BMEP with this engine configuration. With respect to the design of the engine block, cylinder heads, cylinder head attachment system, main bearing assembly, rod bearing assembly and pistons, the engine was originally designed for considerably higher cylinder pressures and other stresses than would be required than the 27-bar BMEP used by EPA within the FRM.

Technical direction from EPA included a peak BMEP limit of 27-bar, which obviated the necessity for some of the reciprocating assembly, engine block, and cylinder head measures taken with the EBDI engine. Taking into account the capabilities of the combustion system, valvetrain configuration, EGR system, and reduced BMEP levels, Ricardo recommended a small increase in compression ratio (from 10:1 to 10.5:1) while maintaining protection for in-use fuel octanes of approximately 91 RON (e.g. 87 AKI E10). All fuel consumption results developed in the Ricardo Study assumed use of U.S. Certification Gasoline (95 RON, E0). A fuel consumption improvement of 3.5 percent was also applied to account for continued application of friction reduction from a combination of technology advances, including piston ring-pack improvements, bore finish improvements, low-friction coatings, improved valvetrain components, bearings improvements, and lower-viscosity crankcase lubricants. The FMEP and fuel consumption improvements were relative to a MY2008 level of technology. BMEP levels were held approximately constant for particular classes of engines within EPA's FRM analyses and analyses for the Draft TAR. Boosting requirements over the reduced operational range for TDS24 (up to 24-bar BMEP) were assumed to be achievable using a VNT within EPA's analyses for the Draft TAR and Proposed Determination. Sequential turbocharging was maintained for TDS27 within EPA analyses for the FRM, but consistent with both the Draft TAR and public comments thereto, TDS27 was not included within the analyses for the Proposed Determination.

Ford commented that with the removal of TDS27 from the analysis, EPA effectiveness values are now closer to industry estimates although still optimistic. Ford believes that it is due to the use of high octane fuel, optimistic friction reductions and failure to account for the effect of higher boost pressures on crevice losses, friction and compression ratio. We disagree with these conclusions. EPA based the effectiveness of these technologies on typical real world operation where use of high octane fuel is largely unnecessary. The use of high octane fuel may be recommended by the manufacturer in some applications and operational conditions as already specified in current production Ford products with similar turbocharged downsized engines as indicated above in the discussion of fuels in Chapter 2.3.1.3 (Fuels).

As discussed above, we believe that EPA's friction reduction assumptions are possible with a combination of friction reduction technology advances not currently used in most engine designs. As discussed, this includes coatings and use of other materials and technologies throughout the engines moving components. The EGRB engine upon which TDS24 is based was originally designed for higher peak cylinder pressures and for a maximum of 30-bar BMEP, thus the main and rod bearings were designed for significantly higher loads than would be encountered at peak BMEP of 24-bar. The friction reduction applied as part of the Ricardo analysis is thus applied to an engine already having higher somewhat FMEP due to the increased size of the main and rod bearings necessary to support operation at 30-bar peak BMEP.

While not directly discussed in our assessment, the impacts of designing engines for higher boost pressures on crevice losses, friction and compression ratio is indirectly incorporated into the final effectiveness estimates as reflected in the engine maps used for estimating effectiveness for the TDS packages. Crevice volumes impacts are generally fundamentally controlled by the manufacturer's design of cylinders and particularly the piston and piston rings. While it is possible that higher boost pressures can have a negative effect on efficiency due to crevice volumes, there are many design solutions a manufacturer can implement to the piston to mitigate any crevice volume penalty. Some of these solutions have been used by manufacturers for many years to reduce crevice volume impacts to other engine emissions, particularly hydrocarbon emissions. Similarly, higher boost can impact friction and have compression ratio implications however manufacturers have the opportunity during the design and development of an engine to determine the appropriate technology solutions to these challenges.

FCA commented that the benefit of cEGR is overestimated due to higher accessory loads and heat rejection. FCA did not provide sufficient information or substantiating data regarding their concern. We believe that properly designed cEGR systems are in production today on several engines from different manufacturers and with appropriate heat exchanger and cooling system design, heat rejection is not an issue.

Figure 2.112 contains a graphical example of how BSFC maps were developed by Ricardo and EPA for varying displacements of TDS24.

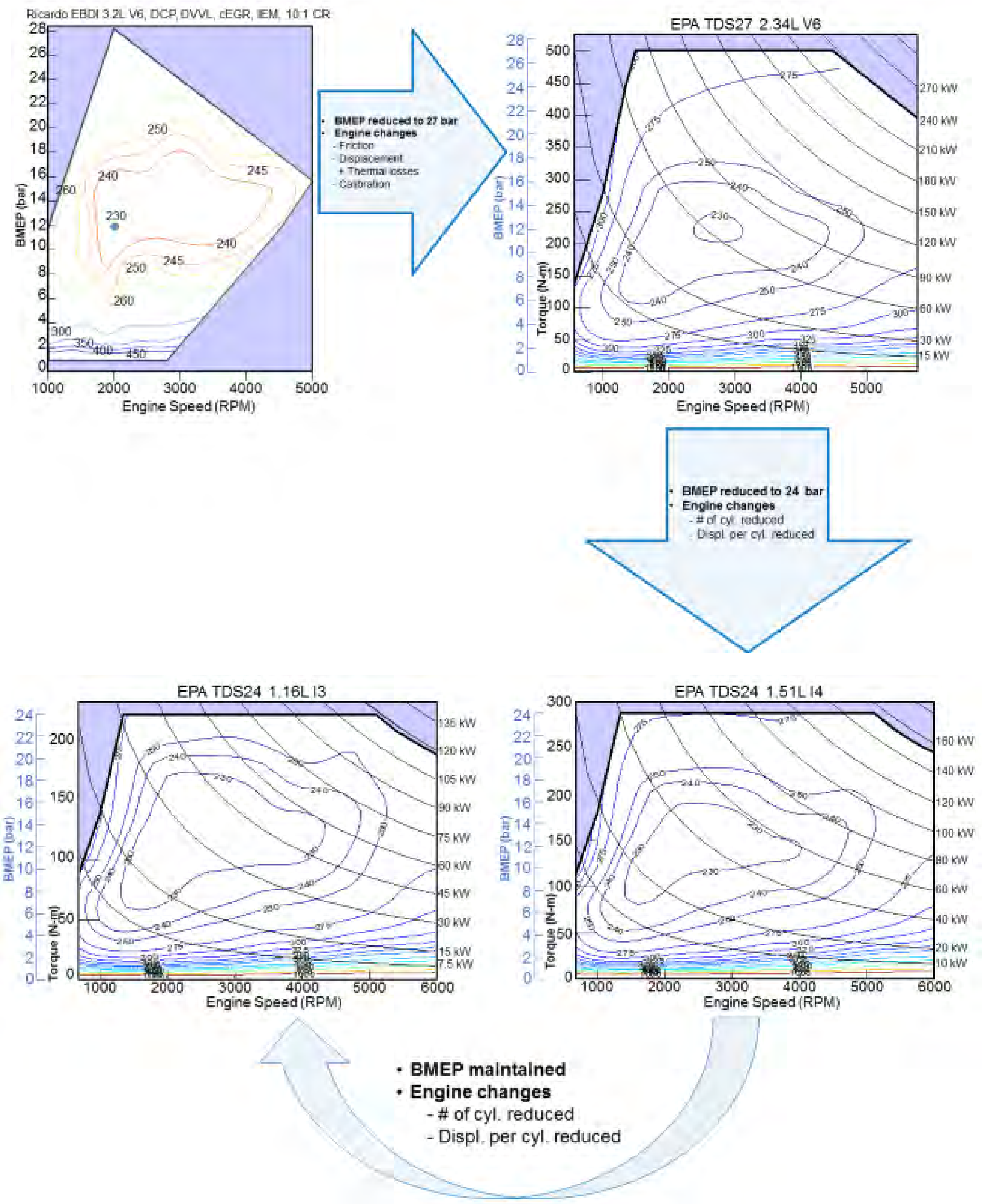


Figure 2.112 Schematic Representation of the Development of BSFC Mapping for TDS24

The brake thermal efficiency (BTE) of the modeled and scaled TDS24 engine maps are compared to contemporary, current production turbocharged engines in Figure 2.113 through Figure 2.115. [581,582,583,584,585]

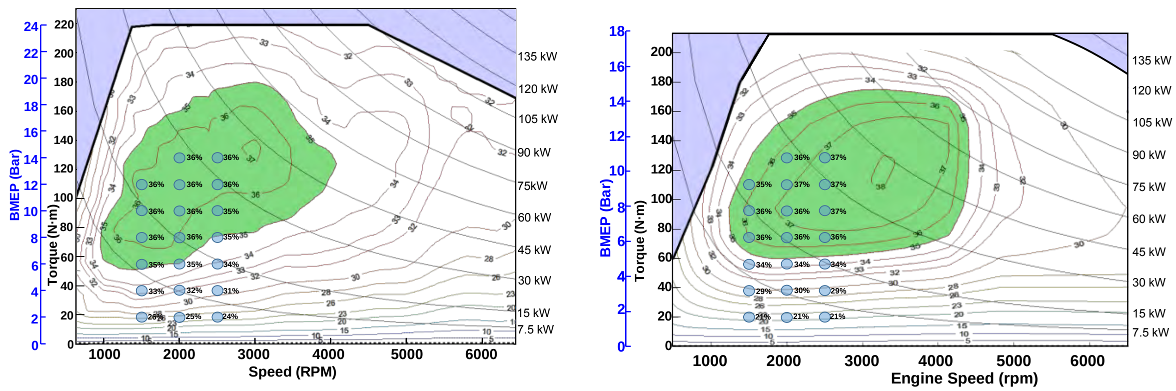


Figure 2.113 Comparison between a 1.15L I3 version of TDS24 (left)KKK and the Honda L15B7 1.5L turbocharged, GDI engine used in the 2017 Civic (right)LLL.

Dark green shading denotes areas of BTE>35%. The Honda specifies use of gasoline with an octane of 87 AKI for the 2017 Civic with the L15B7 engine. Data shown is for operation using >95 RON gasoline in both cases.

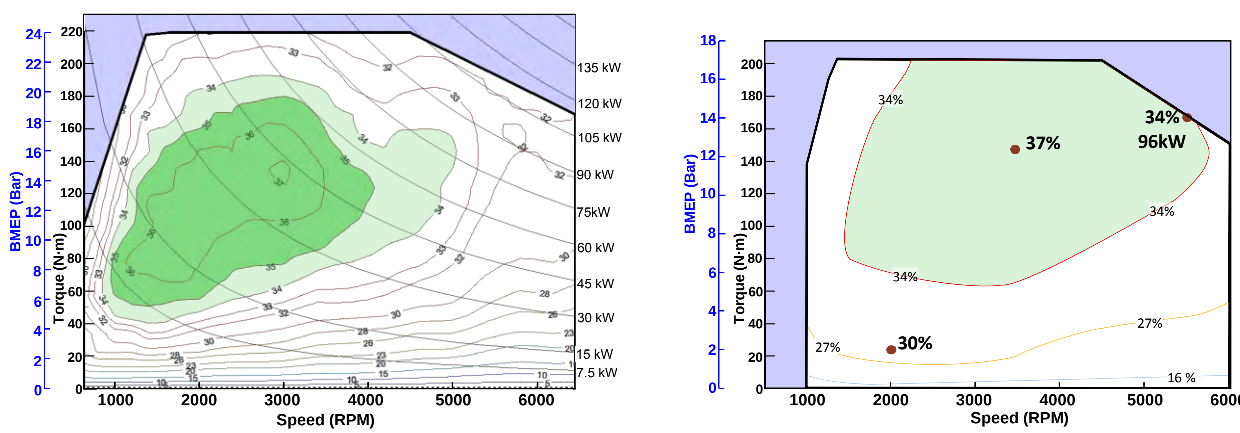


Figure 2.114 Comparison between a 1.15L I3 version of TDS24 (left)MMM and the 2017 Golf 1.5L EA211 TSI EVO EngineNNN.

Light-green shading denotes areas of BTE>34%. Dark green shading denotes areas of BTE>35%. The area of BTE>35% for the VW EA211 is not discernable due to the coarseness of the data provided by the originally published source.

KKK Adapted from Ricardo Study modeling results.
LLL Adapted from Wada et al. 2016 and Nakano et al 2016.
MMM Adapted from Ricardo Study modeling results.
NNN Adapted from Eichler et al. 2016.

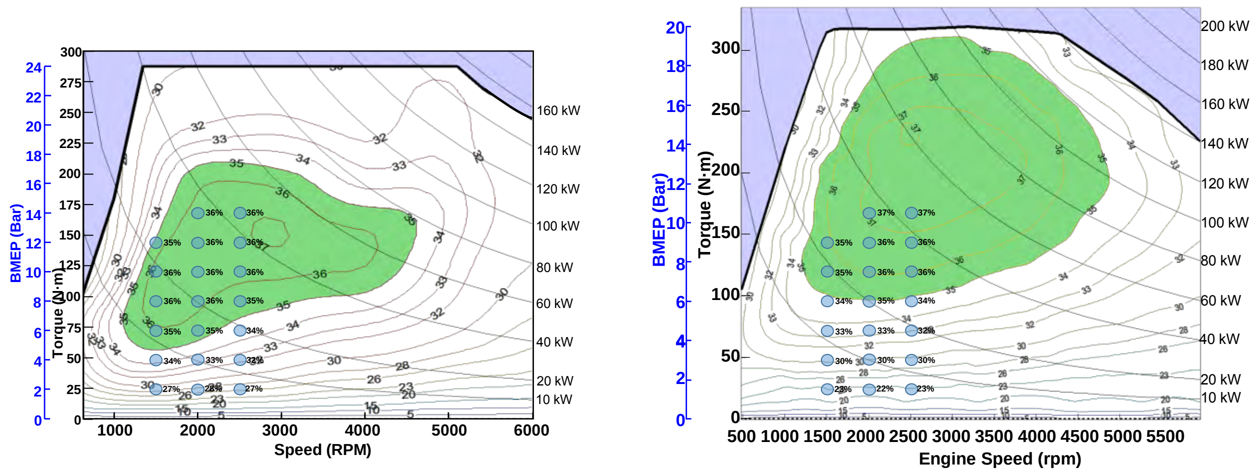


Figure 2.115 Comparison between a 1.51L I3 version of TDS24 (left)[MMM] and the 2017 Audi A3 2.0L 888-3B Engine (right)[OOO].

Dark green shading denotes areas of BTE>35%.

The Honda 1.5L L15B7 turbocharged GDI engine (Figure 2.113) achieves higher peak break thermal efficiency than TDS24, and has a larger area of operation above 35 percent BTE. TDS24 had improved efficiency at low-speed, light load conditions, possibly from pumping loss improvements due to the use of discrete variable valve lift and cooled external EGR, which the Honda L15B7 lacks.

The 2017 VW EA211 TSI EVO engine (Figure 2.114) appears to have a broader area of operation above 34 percent BTE than TDS24 and the BTE reported at 2-bar, 2000 rpm of 30 percent is higher than the corresponding operational point with TDS24. The coarseness of published BTE map for the VW EA211 precludes further comparison. The larger 2.0L VW EA888-3B engine was compared with a 1.51L variant of TDS24.

The VW EA888-3B engine (Figure 2.115) had a significantly larger area of operation above 35 percent BTE. Similar to the Honda comparison, TDS24 had improved efficiency at low-speed, light load conditions; possibly due to pumping loss reduction due to the greater extent of boosting and displacement downsizing and the use of discrete variable valve lift.

On the whole, contemporary turbocharged engines can achieve higher peak BTE and high BTE over a broader range of engine operating conditions than TDS24 modeling results. TDS24 shows improved BTE at lower speeds and lighter loads due to the use of technologies that are either just now entering production (cEGR) or that have been in production for some vehicle applications for over a two decades (VVL). Further development of contemporary turbocharged engines from 2017 to 2025, including use of more advanced boosting systems (e.g., VNT or series sequential turbochargers), engine downsizing to 22-bar BMEP or greater, use of external cooled EGR, combustion system improvements and use of variable valve lift systems would further improve low-speed, light load pumping losses. These improvements would allow current turbocharged/downsized engines to meet or exceed the BTE modeled for TDS24 through

[OOO] Adapted from Wurms et al. 2015.

incremental developmental improvements (e.g., VVL, cEGR) with sufficient lead time to meet the 2025 light-duty GHG standards.

In comments regarding octane impacts on vehicles with turbocharged, downsized engines, AAM cited data from an SAE technical paper (SAE 2014-01-1228) showing impacts on CO_2 emissions for three different octane levels (91 RON, 96 RON, 101 RON) levels. The overall implications were that AAM believed CO_2 emissions from operation on lower octane fuels such as Tier 3 gasoline or similar in-use gasolines would result in higher CO_2 emissions than using Tier 2 gasoline with approximately 96 RON as used during the development of EPA's turbocharged/downsized technology effectiveness.

In reviewing the paper cited by AAM, it became clear that the properties of the fuels tested bore little resemblance to the properties of either Tier 2 or Tier 3 gasoline properties, or the average properties of current in-use regular-grade gasoline (upon which Tier 3 gasoline is based). The study cited by AAM was actually designed to investigate the use of mid-level ethanol blends at different octane levels, not to investigate CO_2 emissions from fuels used for emissions compliance testing or for current in-use grades of gasoline. For example, the 96 RON fuel tested was not E0 (e.g., Tier 2 gasoline) – it was blended to a 20 percent ethanol content (E20). The 101 RON test fuel was blended to a 30 percent ethanol content (E30). The 91 RON fuel that was tested may have been either E10 or E20 – AAM does not make this clear in their discussion of the data from SAE 2014-01-1228, nor does it characterize the higher octane fuels as being mid-level ethanol blends. Mid-level ethanol blends like E20 and E30 are not approved for use in light-duty vehicle applications in the U.S. with the sole exception of flex-fuel-vehicles.

While the observed trends may be valid for the range of fuel properties investigated within the cited study, AAM shared no data using fuels having properties similar to those used either for current CO2 compliance (e.g., Tier 2 gasoline), future Tier 3 criteria pollutant compliance (e.g., Tier 3 gasoline), or having properties comparable to average values for U.S. in-use "Regular" pump-grade gasoline (87 AKI E10 or approximately Tier 3 gasoline) or other commonly available grades of gasoline (e.g., 93 AKI E10). Ethanol content, distillation properties, carbon content and aromatic content all have potential impacts on CO_2. Octane can also impact CO_2 emissions depending on the drive cycle used and vehicle road load for a particular application.

AAM's discussed relationships between the CO_2 data for the mid-level ethanol blended gasolines relative to a parameter described as "displacement over mass ratio" or D/M. AAM indicated on one chart that this represented "Liters per tonne". EPA assumed this to be liters of cylinder displacement per U.S. ton (2000 pounds) relative to dynamometer test inertia, but AAM did not indicate if vehicle mass within the ratio represented curb weight, a loaded vehicle weight, a test weight, or a dynamometer inertia category, or if "tonne" refers to "metric tonne" (1000 kg) or "U.S. Ton" (2000 lbm).

AAM stated that "Using 91 RON fuel (e.g. Tier 3 fuel) there is no further CO2 benefit below a displacement-over-mass ratio (D/M) of about 0.9. However, as shown by the 96 RON and 101 RON data in the figure below, the Agency assumptions based on higher octane fuel would indicate that additional downsizing beyond 0.9 D/M still yields reductions in CO2." As part of their compliance with GHG regulations, manufacturers already downsize engines significantly below D/M of 0.9 L/ton for a number of light-duty vehicle and light-duty truck applications. A partial summary of MY2015 vehicles using turbocharged/downsized engines and having D/M of less than 0.9 L/ton is shown in Table 2.70. Vehicles at D/M below 0.9 L/ton were predominantly passenger cars. The light trucks with D/M at or below 0.9 consisted of cross-over sport-utility vehicles.

Table 2.70 Partial summary of MY2015 vehicles with D/M at or below 0.9 L/ton.

Rows in **BOLD, yellow** denote vehicles using engines above 20-bar BMEP.

D/M	Manufacturer	Short Description	Displacement (L)	BMEP (bar)	Fuel Requirements (R-Regular, P-premium)
0.62	**Ford**	**Focus SFE FWD**	**1.0**	**25**	**R**
0.62	**Ford**	**FOCUS FWD**	**1.0**	**25**	**R**
0.70	**Ford**	**Fiesta SFE FWD**	**1.0**	**25**	**R**
0.80	**FCA**	**500L**	**1.4**	**22**	**R**
0.80	GM	ENCORE AWD	1.4	18	R
0.80	GM	TRAX AWD	1.4	18	R
0.80	**FCA**	**Renegade 4x4**	**1.4**	**22**	**R**
0.80	**Ford**	**FUSION FWD**	**1.5**	**21**	**R**
0.81	GM	ENCORE	1.4	18	R
0.81	GM	TRAX	1.4	18	R
0.83	Ford	TRANSIT CONNECT WAGON FWD	1.6	20	R
0.83	**FCA**	**Dart**	**1.4**	**22**	**R**
0.83	**FCA**	**Dart Aero**	**1.4**	**22**	**R**
0.83	**FCA**	**500L**	**1.4**	**22**	**R**
0.83	**FCA**	**Renegade 4x2**	**1.4**	**22**	**R**
0.84	**Ford**	**EXPLORER FWD**	**2.0**	**23**	**R**
0.84	**Ford**	**MKT FWD**	**2.0**	**23**	**R**
0.85	Ford	Transit Connect Van 2WD	1.6	20	R
0.87	GM	CRUZE	1.4	18	R
0.87	GM	CRUZE ECO	1.4	18	R
0.87	GM	SONIC	1.4	18	R
0.87	GM	SONIC RS	1.4	18	R
0.87	GM	SONIC 5	1.4	18	R
0.87	GM	SONIC 5 RS	1.4	18	R
0.88	**Audi**	**Q5**	**2.0**	**23**	**R**
0.88	**Audi**	**A5 Cabriolet Quattro**	**2.0**	**22**	**R**
0.89	**Ford**	**EDGE AWD**	**2.0**	**23**	**R**
0.89	**JLR**	**Discovery Sport**	**2.0**	**21**	**P**
0.89	**JLR**	**LR2**	**2.0**	**21**	**P**
0.89	**BMW**	**X4 xDrive28i**	**2.0**	**22**	**P**
0.89	**BMW**	**428i xDrive Convertible**	**2.0**	**22**	**P**
0.89	**Ford**	**EDGE FWD**	**2.0**	**23**	**R**

EPA effectiveness assumptions were based upon the use of Tier 2 E0 gasoline, as required for demonstration of compliance with Federal light-duty GHG standards over the combined-cycle test. Tier 2 E0 gasoline has properties that differ significantly from the 96 RON E20 gasoline in the data used within AAM's comments. Tier 3 E10 91 RON gasoline and in-use 87 AKI regular-grade gasoline also have properties that differ significantly from the E10 and E20 gasolines cited in AAM's comments, including distillation differences and differences in carbon content. Aromatic content and net heat of combustion, important properties in determining fuel impacts, were not reported in the work cited by AAM.

To investigate fuel impacts on CO2 emissions from turbocharged/downsized engines, EPA conducted chassis dynamometer testing with a pickup truck having the highest BMEP turbocharged light-duty truck engine currently in production (Ford F150 2.7L Ford EcoBoost, 6-speed automatic transmission) and with a light-duty vehicle having the highest peak brake thermal efficiency turbocharged downsized engine currently available in the U.S. (Honda Civic L15B7 with 1.5L engine turbocharged, GDI engine, CVT). Testing was conducted using a Tier 2 E0 96RON/93 AKI gasoline and using a Tier 3 E10 91 RON/87 AKI gasoline, the latter having properties similar to U.S. national average values for 87 AKI E10 in-use gasoline. Properties for these two fuels are summarized in Appendix D of this TSD. The 2015 Ford F150 had a D/M of approximately 1.1 L/ton while the 2017 Honda Civic had a D/M of approximately 0.9 L/ton.

The CO2 emission results from the testing are summarized in Table 2.71. The chassis dynamometer testing demonstrated a CO2 reduction of just over 1 percent for the 87 RON E10 Tier 3 gasoline relative to the 96 RON E0 Tier 2 gasoline for the combined cycle results. The CO2 differences over the combined cycle were statistically significant at a 95 percent confidence level.

Table 2.71 Summary of CO2 emissions from testing a Ford F150 2.7L turbocharged vehicle and a Honda Civic 1.5L vehicle on Tier 2 and Tier 3 fuels.

Vehicle	Fuel Used	FTP (City)	HWFET (Highway)	Combined
		CO2 (g/mi) [± 95% conf. int.]	CO2 (g/mi) [± 95% conf. int.]	CO2 (g/mi) [± 95% conf. int.]
Ford F150 2.7 EcoBoost 6-sp Auto	Fuel C (Tier 2, E0, 93 AKI)	380.61 [1.67]	244.79 [1.80]	319.49 [1.52]
Ford F150 2.7 EcoBoost 6-sp Auto	Fuel D (Tier 3, E10, 87 AKI)	376.87 [1.74]	241.92 [0.97]	316.14 [1.34]
% Difference for Fuel D		-0.98%	-1.17%	-1.05%
Significant at 95% Confidence?		Yes	Yes	Yes
Honda Civic 1.5 Turbo CVT	Fuel C (Tier 2, E0, 93 AKI)	216.98 [0.96]	144.75 [0.38]	184.47 [0.60]
Honda Civic 1.5 Turbo CVT	Fuel D (Tier 3, E10, 87 AKI)	213.37 [0.57]	143.16 [0.77]	181.77 [0.30]
% Difference for Fuel D		-1.66%	-1.10%	-1.46%
Significant at 95% Confidence?		Yes	Yes	Yes

The test results were also similar to those found during chassis dynamometer and engine dynamometer testing of a naturally aspirated, non-HEV Atkinson Cycle application by EPA (see section 2.3.4.1.8.1.). A reduction of CO2 emissions from light-duty vehicles over the combined cycle for testing with Tier 3 gasoline relative to Tier 2 gasoline also appears to be a general trend for light-duty vehicles recently tested by EPA. Preliminary test results from 10 MY2013-MY2016 light-duty vehicles (7 passenger cars, 3 light-duty trucks) having a range of combustion systems (GDI, PFI, Atkinson, Turbocharged) all show a similar trend of a small decrease in CO2 emissions over the combined-cycle for Tier 3 gasoline relative to Tier 2 gasoline. Based on EPA testing to date, CO2 emissions from in-use grades of 87 AKI and Tier 3 gasoline result in lower CO2 emissions than results achieved during 2-cycle chassis dynamometer testing using Tier 2 gasoline.

2.3.4.1.9.2 Cost Data Used and Basis for Assumptions

Costs associated with gasoline direct injection are equivalent to those used in the Draft TAR, updated to 2015 dollars. The GDI costs incremental to port-fuel injection for I4, V6 and V8 engines are shown below.

Table 2.72 Costs for Gasoline Direct Injection on an I3 & I4 Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$241	23	$218	$215	$211	$208	$206	$203	$201	$198	$196
IC	Med2	2018	$92	$92	$69	$69	$69	$69	$68	$68	$68
TC			$310	$307	$280	$277	$274	$272	$269	$267	$265

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.73 Costs for Gasoline Direct Injection on a V6 Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$363	23	$328	$323	$319	$314	$310	$306	$302	$299	$296
IC	Med2	2018	$139	$139	$104	$104	$103	$103	$103	$103	$103
TC			$467	$462	$422	$418	$413	$409	$406	$402	$399

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.74 Costs for Gasoline Direct Injection on a V8 Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$436	23	$395	$389	$383	$378	$373	$368	$364	$360	$356
IC	Med2	2018	$167	$167	$125	$125	$124	$124	$124	$124	$124
TC			$562	$556	$508	$502	$497	$492	$488	$484	$480

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with turbocharging are equivalent to those used in the Draft TAR, updated to 2015 dollars. The turbo costs incremental to naturally aspirated I-configuration and V-configuration engines are shown below.

Table 2.75 Costs for Turbocharging, 18/21 bar, I-Configuration Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$457	23	$413	$407	$401	$395	$390	$385	$381	$376	$372
IC	Med2	2018	$175	$175	$131	$130	$130	$130	$130	$130	$130
TC			$588	$581	$531	$526	$520	$515	$511	$506	$502

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.76 Costs for Turbocharging, 18/21 bar, V-Configuration Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$770	23	$697	$686	$676	$666	$658	$649	$642	$634	$628
IC	Med2	2018	$295	$294	$220	$220	$219	$219	$219	$219	$219
TC			$992	$980	$896	$886	$877	$869	$861	$853	$846

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.77 Costs for Turbocharging, 24 bar, I-Configuration Engine & for Miller-cycle I-Configuration Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$730	23	$661	$651	$641	$632	$624	$616	$609	$602	$595
IC	Med2	2024	$280	$279	$279	$278	$278	$278	$277	$277	$207
TC			$941	$930	$920	$911	$902	$894	$886	$879	$803

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.78 Costs for Turbocharging, 24 bar, V-Configuration Engine & for Miller-cycle V-Configuration Engine (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$1,245	23	$1,127	$1,110	$1,093	$1,078	$1,064	$1,050	$1,038	$1,026	$1,015
IC	Med2	2024	$477	$476	$475	$475	$474	$473	$473	$472	$354
TC			$1,604	$1,586	$1,568	$1,553	$1,538	$1,524	$1,511	$1,499	$1,369

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with engine downsizing are equivalent to those used in the Draft TAR, updated to 2015 dollars. The downsizing costs incremental to the baseline engine configuration are shown below.

Table 2.79 Costs for Downsizing as part of Turbocharging & Downsizing (dollar values in 2015$)

Downsizing from & to	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
I4 DOHC to I3	DMC	-$218	23	-$197	-$194	-$192	-$189	-$186	-$184	-$182	-$180	-$178
I4 DOHC to I4	DMC	-$96	23	-$87	-$86	-$84	-$83	-$82	-$81	-$80	-$79	-$78
V6 DOHC to I4	DMC	-$618	23	-$560	-$551	-$543	-$535	-$528	-$522	-$516	-$510	-$504
V6 SOHC to I4	DMC	-$432	23	-$391	-$385	-$379	-$374	-$369	-$365	-$360	-$356	-$352
V6 OHV to I4	DMC	$305	28	$298	$292	$286	$281	$276	$272	$268	$264	$261
V8 DOHC to V6	DMC	-$310	23	-$280	-$276	-$272	-$268	-$264	-$261	-$258	-$255	-$252
V8 SOHC 3V to V6	DMC	-$175	23	-$159	-$156	-$154	-$152	-$150	-$148	-$146	-$145	-$143
V8 SOHC to V6	DMC	-$95	23	-$86	-$84	-$83	-$82	-$81	-$80	-$79	-$78	-$77
V8 OHV to V6	DMC	$356	28	$348	$340	$334	$328	$322	$317	$313	$308	$304
I4 DOHC to I3	IC	Med2	2018	$84	$83	$62	$62	$62	$62	$62	$62	$62
I4 DOHC to I4	IC	Med2	2018	$37	$37	$27	$27	$27	$27	$27	$27	$27
V6 DOHC to I4	IC	Med2	2018	$237	$236	$177	$177	$176	$176	$176	$176	$176
V6 SOHC to I4	IC	Med2	2018	$166	$165	$124	$123	$123	$123	$123	$123	$123
V6 OHV to I4	IC	Med2	2018	$118	$118	$88	$88	$87	$87	$87	$87	$87
V8 DOHC to V6	IC	Med2	2018	$119	$118	$88	$88	$88	$88	$88	$88	$88
V8 SOHC 3V to V6	IC	Med2	2018	$67	$67	$50	$50	$50	$50	$50	$50	$50
V8 SOHC to V6	IC	Med2	2018	$36	$36	$27	$27	$27	$27	$27	$27	$27
V8 OHV to V6	IC	Med2	2018	$137	$137	$102	$102	$102	$102	$102	$102	$102
I4 DOHC to I3	TC			-$114	-$111	-$129	-$127	-$124	-$122	-$120	-$118	-$116
I4 DOHC to I4	TC			-$50	-$49	-$57	-$56	-$55	-$54	-$53	-$52	-$51
V6 DOHC to I4	TC			-$323	-$315	-$366	-$359	-$352	-$346	-$340	-$334	-$329
V6 SOHC to I4	TC			-$226	-$220	-$256	-$251	-$246	-$242	-$237	-$233	-$230
V6 OHV to I4	TC			$416	$409	$374	$369	$364	$359	$355	$351	$348
V8 DOHC to V6	TC			-$162	-$158	-$183	-$180	-$176	-$173	-$170	-$167	-$165
V8 SOHC 3V to V6	TC			-$92	-$89	-$104	-$102	-$100	-$98	-$96	-$95	-$93
V8 SOHC to V6	TC			-$49	-$48	-$56	-$55	-$54	-$53	-$52	-$51	-$50
V8 OHV to V6	TC			$485	$478	$436	$430	$424	$419	$414	$410	$406

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs;
the downsized configuration is always a DOHC.

Costs associated with turbocharging combined with engine downsizing (TDS) are similarly equivalent to those used in the Draft TAR, updated to 2015 dollars. The TDS costs incremental to the baseline engine configuration are shown below. Note that the costs presented below do not include direct injection costs or other possible technologies such as cooled EGR. The costs presented are simply the combination of the above turbo costs and downsizing costs.

Table 2.80 Costs for Turbocharging & Downsizing (2015$)

Turbo	Downsize		2017	2018	2019	2020	2021	2022	2023	2024	2025
TURB18-I	I4 to I3	TC	$474	$470	$402	$399	$396	$393	$391	$388	$386
TURB18-I	I4 DOHC to I4	TC	$538	$533	$475	$470	$466	$462	$458	$454	$451
TURB18-I	V6 DOHC to I4	TC	$265	$267	$165	$167	$168	$170	$171	$172	$173
TURB18-I	V6 SOHC to I4	TC	$363	$362	$276	$275	$274	$274	$273	$273	$272
TURB18-I	V6 OHV to I4	TC	$1,004	$991	$905	$894	$884	$875	$866	$857	$850
TURB18-V	V8 DOHC to V6	TC	$830	$823	$712	$706	$701	$696	$691	$686	$682
TURB18-V	V8 SOHC 3V to V6	TC	$900	$891	$792	$784	$777	$771	$764	$758	$753
TURB18-V	V8 SOHC to V6	TC	$942	$932	$840	$831	$823	$816	$809	$802	$796
TURB18-V	V8 OHV to V6	TC	$1,477	$1,458	$1,332	$1,316	$1,301	$1,288	$1,275	$1,263	$1,252
TURB24-I	I4 to I3	TC	$827	$819	$791	$784	$778	$772	$766	$761	$687
TURB24-I	I4 DOHC to I4	TC	$891	$881	$863	$855	$847	$840	$833	$827	$752
TURB24-I	V6 DOHC to I4	TC	$618	$615	$554	$552	$550	$548	$546	$545	$474
TURB24-I	V6 SOHC to I4	TC	$715	$710	$664	$660	$656	$652	$649	$645	$573
TURB24-I	V6 OHV to I4	TC	$1,357	$1,339	$1,294	$1,279	$1,266	$1,253	$1,241	$1,230	$1,150
TURB24-V	V8 DOHC to V6	TC	$1,442	$1,428	$1,385	$1,373	$1,362	$1,351	$1,341	$1,331	$1,204
TURB24-V	V8 SOHC 3V to V6	TC	$1,512	$1,496	$1,465	$1,451	$1,438	$1,426	$1,414	$1,404	$1,275
TURB24-V	V8 SOHC to V6	TC	$1,555	$1,537	$1,512	$1,498	$1,484	$1,471	$1,459	$1,447	$1,318
TURB24-V	V8 OHV to V6	TC	$2,089	$2,063	$2,005	$1,983	$1,962	$1,943	$1,925	$1,908	$1,774

Note: TC=total costs; the downsized configuration is always a DOHC.

Costs associated with turbocharging combined with Atkinson-2 technology (i.e., Miller-cycle) are presented below. Note that the costs presented below do not include direct injection costs or other required technologies such as cooled EGR. The costs presented are simply the combination of the above turbo costs and Atkinson-2 costs presented in Section 2.3.4.1.8. Note also that the ATK2 engine as shown in the table is always a DOHC configuration engine so also not included in the table are the costs associated with converting, for example, a SOHC or OHV engine to a DOHC configuration. Those costs are presented below following the cooled EGR costs. The costs used here are identical to those used in the Draft TAR, updated to 2015 dollars.

Table 2.81 Costs for Miller Cycle (2015$)

Turbo	ATK2 engine		2017	2018	2019	2020	2021	2022	2023	2024	2025
TURB24-I	I3	TC	$1,087	$1,074	$1,062	$1,051	$1,040	$1,029	$1,020	$1,010	$923
TURB24-I	I4	TC	$1,087	$1,074	$1,062	$1,051	$1,040	$1,029	$1,020	$1,010	$923
TURB24-V	V6	TC	$1,824	$1,802	$1,782	$1,763	$1,745	$1,728	$1,711	$1,696	$1,549
TURB24-V	V8	TC	$1,952	$1,928	$1,906	$1,885	$1,865	$1,846	$1,828	$1,811	$1,655

Note: TC=total costs; the downsized configuration is always a DOHC.

Costs associated with cooled EGR are equivalent to those used in the Draft TAR, updated to 2015 dollars. The cooled EGR costs incremental to the baseline engine configuration are shown below.

Table 2.82 Costs for Cooled EGR (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025

DMC	$265	23	$240	$237	$233	$230	$227	$224	$221	$219	$216
IC	Med2	2024	$102	$102	$101	$101	$101	$101	$101	$101	$75
TC			$342	$338	$334	$331	$328	$325	$322	$320	$292

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with converting non-DOHC engines to a DOHC configuration without any engine downsizing are equivalent to those used in the Draft TAR, updated to 2015 dollars. These costs are used when converting a non-DOHC engine to a DOHC configuration when downsizing is not also included. The primary example for this Proposed Determination analysis is converting to a DOHC configuration to enable Atkinson-2 technology. The costs are presented below and do not include other potential technologies such as variable valve timing or lift or cylinder deactivation, all of which are accounted for separately by EPA.

Table 2.83 Costs for Valvetrain Conversions from non-DOHC to DOHC (dollar values in 2015$)

Conversion	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
V6 SOHC to V6 DOHC	DMC	$186	23	$169	$166	$164	$161	$159	$157	$155	$154	$152
V6 OHV to V6 DOHC	DMC	$534	28	$522	$511	$501	$492	$484	$476	$469	$462	$456
V8 SOHC 3V to V8 DOHC	DMC	$134	23	$121	$119	$118	$116	$115	$113	$112	$111	$109
V8 SOHC to V8 DOHC	DMC	$215	23	$195	$192	$189	$186	$184	$181	$179	$177	$175
V8 OHV to V8 DOHC	DMC	$585	28	$571	$559	$549	$539	$530	$521	$514	$506	$500
V6 SOHC to V6 DOHC	IC	Med2	2018	$71	$71	$53	$53	$53	$53	$53	$53	$53
V6 OHV to V6 DOHC	IC	Med2	2018	$206	$206	$154	$153	$153	$153	$153	$152	$152
V8 SOHC 3V to V8 DOHC	IC	Med2	2018	$51	$51	$38	$38	$38	$38	$38	$38	$38
V8 SOHC to V8 DOHC	IC	Med2	2018	$82	$82	$61	$61	$61	$61	$61	$61	$61
V8 OHV to V8 DOHC	IC	Med2	2018	$226	$225	$168	$168	$168	$167	$167	$167	$167
V6 SOHC to V6 DOHC	TC			$240	$237	$217	$215	$212	$210	$208	$207	$205
V6 OHV to V6 DOHC	TC			$728	$716	$654	$645	$637	$629	$622	$615	$609
V8 SOHC 3V to V8 DOHC	TC			$173	$171	$156	$154	$153	$151	$150	$149	$147
V8 SOHC to V8 DOHC	TC			$277	$274	$250	$247	$245	$243	$240	$238	$236
V8 OHV to V8 DOHC	TC			$797	$785	$717	$707	$697	$689	$681	$673	$667

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs;
the downsized configuration is always a DOHC.

2.3.4.1.9.3 Basis for Feasibility Assumptions

Between 2010 and 2015, automotive manufacturers have been adopting advanced powertrain technologies in response to GHG and CAFE standards. Just over 45 percent of MY2015 light-duty vehicles in U.S. were equipped with gasoline direct injection (GDI) and approximately 18 percent of MY2015 light-duty vehicles were turbocharged. Nearly all vehicles using turbocharged spark-ignition engines also used GDI to improve suppression of knocking combustion. GDI provides direct cooling of the in-cylinder charge via in-cylinder fuel vaporization. Use of GDI allows an increase of compression ratio of approximately 0.5 to 1.5 points relative to naturally aspirated or turbocharged engines using port-fuel-injection (e.g., an increase from 9.9:1 for the 5.3L PFI GM Vortec 5300 to 11:1 for the 5.3L GDI GM Ecotec3 with similar 87 AKI gasoline octane requirements).

Many automotive manufacturers have launched a third or fourth generation of GDI engines since their initial introduction in the U.S. in 2007. Turbocharged, GDI engines are in now in volume production at between 21-bar and 25-bar BMEP. VW/Audi, FCA, Ford and more recently (MY2016) GM have all introduced engines with 21-25 bar BMEP in both passenger car and light-truck platforms. The 2.7L EcoBoost engine available in the segment-leading 2017 Ford F150 pickup has just over 24-bar peak BMEP and a maximum loaded trailer weight towing capacity in excess of 7,600 pounds. The 3.5L EcoBoost engine, also available in the 2017 Ford F150, has a peak BMEP of 23-bar and a maximum loaded trailer weight towing capacity in excess of 10,600 pounds.

Most recent turbocharged engine designs now use head-integrated, water-cooled exhaust manifolds and coolant loops that separate the cooling circuits between the engine block and the head/exhaust manifold(s). Head-integrated exhaust manifolds (IEM) are described further in the section on thermal management in 2.2.2.11. The use of IEM was assumed within the EPA analysis of 27-bar BMEP turbocharged GDI engines for the FRM and is assumed for all TDS24 (24-bar BMEP) engines in the Draft TAR and Proposed Determination analyses. The benefits, including increased ability to downspeed the engine without pre-ignition and the potential for cost savings in the design of the turbocharger turbine housing appear to extend to lower BMEP-level turbocharged GDI engines and will likely be incorporated into many future turbocharged light-duty vehicle applications. The application of IEMs does effect cooling system design and manufacturers will be required to provide sufficient cooling system capacity if they adopt this technology. Recent turbocharger improvements have included use of lower-mass, lower inertia components and lower friction ball bearings to reduce turbocharger lag and enable higher peak rotational speeds. Improvements have also been made to turbocharger compressor designs to improve compressor efficiency and to expand the limits of compressor operation by improving surge characteristics.

2.3.4.2 Transmissions: Data and Assumptions for this Proposed Determination

In assessing the effectiveness of transmission technology, EPA used multiple data sources. These data sources include benchmarking activities, conducted at both the National Vehicle and Fuel Emissions Lab (NVFEL) in Ann Arbor, Michigan and through contract work, technical literature, technical conferences, vehicle certification data and stakeholder meetings. To ensure the data were consistent, it was important to understand the assumptions made in determination of the effectiveness. It is also important to note the engine with which the transmission is being paired. Since much of the effectiveness associated with advanced transmissions is in the transmission's ability to alter the operation range of the engine, and thus minimize pumping losses, the engine efficiency in the area of operation is a major part of the effectiveness calculation. The National Academy of Sciences, in their 2015 report, noted that "as engines incorporate new technologies to improve fuel consumption, including variable valve timing and lift, direct injection, and turbocharging and downsizing, the benefits of increasing transmission ratios or switching to a CVT diminish."[586] This is not to say that transmissions are not an important technology going forward, but rather a recognition that future engines will have larger "islands" of low fuel consumption that potentially rely less on the transmission to improve the overall efficiency of the vehicle. Thus, effectiveness percentages reported for transmissions paired with unimproved engines would be expected to be reduced when the same transmission is paired with a more advanced engine. Regardless of the engine with which a particular transmission is mated, it is expected that vehicle manufacturers and suppliers will continue to improve the overall efficiency of the transmission itself by reducing friction and parasitic losses.

2.3.4.2.1 Assessment and Classification of Automated Transmissions (AT, AMT, DCT, CVT)

As in the Draft TAR, transmissions have again been defined in the analysis as one of four types:[PPP]

- TRX11 - 6-speed with high efficiency gearbox (HEG) level 1
- TRX12 - 6-speed with high efficiency gearbox (HEG) level 2
- TRX21 - 8-speed with high efficiency gearbox (HEG) level 1 and CVTs
- TRX22 - 8-speed with high efficiency gearbox (HEG) level 2 and improved CVTs

This differs from the FRM analysis that maintained each type of transmission separately (AT, DCT, CVT, etc.). This change was implemented by EPA to prevent the analysis from disproportionally implementing transmission changes as technology packages were applied in OMEGA. The 2015 baseline fleet has transmission type (AT, DCT, CVT, etc.) that is linked to each vehicle and is maintained throughout the analysis.

For this Proposed Determination, EPA has assessed the baseline fleet (MY2015, as described in Chapter 1 of this TSD) and have included the following assumptions:

- All manufacturers have incorporated some level of early torque converter lockup, as well as an appropriate level of advanced shift logic, into automatic transmissions with six speeds and above.
- All manufacturers have incorporated some level gearbox efficiency improvements (termed as "high efficiency gearbox" or HEG), and advanced shift logic (termed "advanced shift logic" or ASL) into automatic transmissions with six speeds and above, and CVTs.
- All types of automated transmissions have the potential to improve between now and 2025 MY. EPA expects that gains in efficiency can be made, independent of the transmission type. Figure 2.116 shows that all three of the main transmission types (AT, DCT, CVT) moving across their respective paths toward their ultimate level of efficiency. The term "Flexibility" here denotes how well the transmission can keep the engine on its optimal efficiency line.

[PPP] Each of these speed or gear designations should be taken to mean the approximate gear-ratio spread and, therefore, inclusive of CVTs.

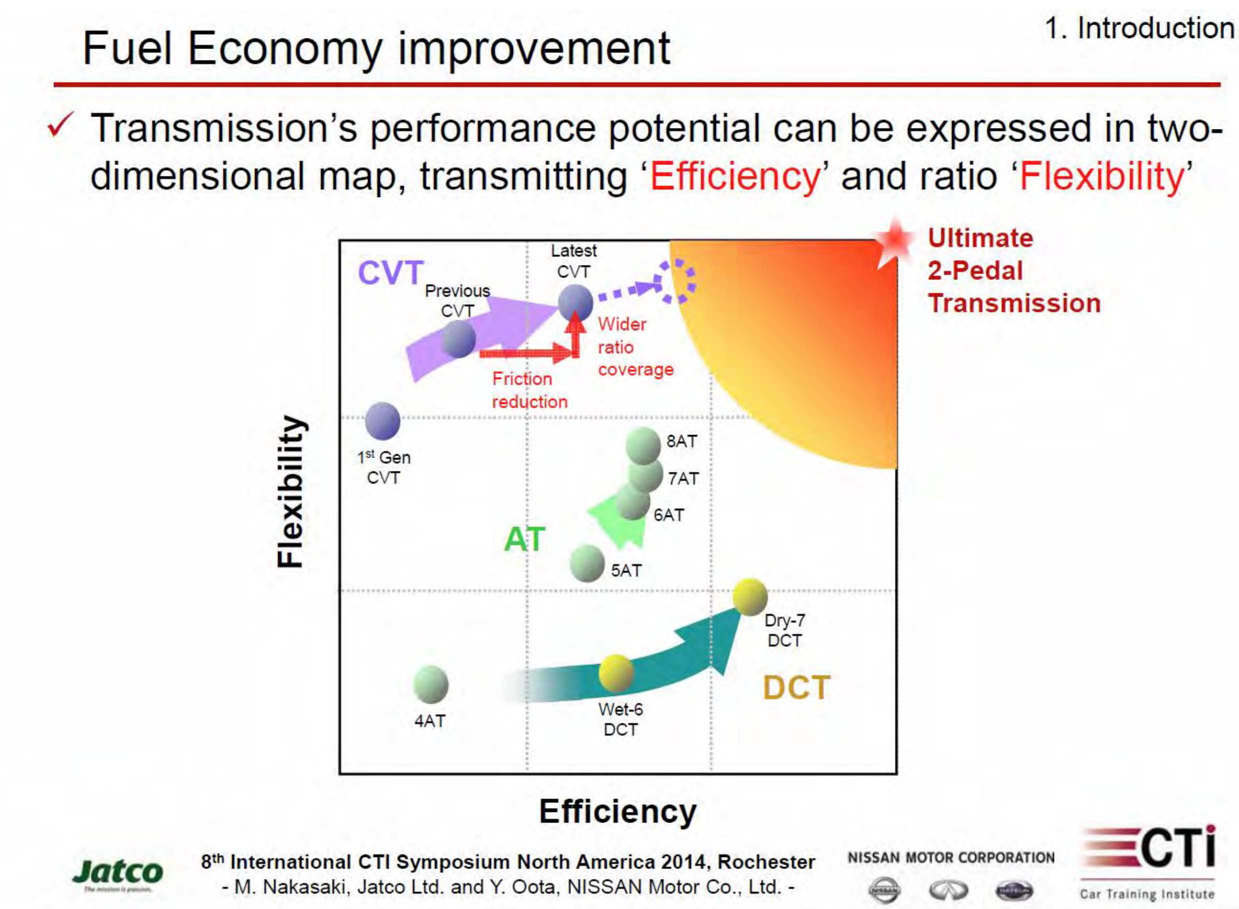


Figure 2.116 Comparison of the Different Transmission Types

- The incremental effectiveness and cost for all automated transmissions are based on data from conventional automatics.

EPA does not believe that the technologies represented by HEG and ASL have been incorporated into all transmissions in the 2015 fleet, but are presumed to be included in both the base 6-speed and higher-gear transmissions, and CVTs in the 2015 fleet.

Under the premise that automated transmissions that are currently in the fleet demonstrate different effectiveness, and with the expectation that all automated transmissions will be improved between now and 2025 MY, 2015 transmissions were mapped to three different designations: Null, TRX11 and TRX21. Table 2.84 shows the mapping between the existing transmissions in the 2015 baseline fleet and the transmission designations that have been established for this Proposed Determination analysis. Note that manual transmission designations were left alone unless the vehicle was determined to need electrification in order to comply in which case it would be upgraded to either a hybrid or electric vehicle transmission.

Table 2.84 Transmission Level Map

Trans code from Data	Transmission Type	Number of Gears	Transmission Level
A	Automatic	4	Null

A	Automatic	5	Null
A	Automatic	6	TRX11
A	Automatic	7	TRX21
A	Automatic	8	TRX21
A	Automatic	9	TRX21
AM	Automated Manual	5	Null
AM	Automated Manual	6	TRX11
AM	Automated Manual	7	TRX21
C	CVT	0	TRX21
D	Dual Clutch	6	TRX11
D	Dual Clutch	7	TRX21

In the "TRX" numbering system the first digit specifies the number of gears in the transmission and the second digit specifies the HEG level. A "1" in the first digit represents a six speed transmission and a "2" in the first digit represents an eight speed. Similarly, a "1" in the second digit represents HEG1 and a "2" in the second digit represents HEG2. An important aspect of using the TRX system is that it meant to estimate the effectiveness of both the current transmission technology and future transmission technology. This is appropriate because it allows EPA to account for technology already found in the baseline fleet, as well as apply future transmission technology as a means of improving vehicle efficiency. With the predominant transmission type in the 2015 MY baseline fleet (70.8 percent) being a conventional automatic transmission. EPA believes that this approach most closely approximates the overall incremental effectiveness and cost associated with all automated transmissions. In the future, if a particular transmission technology develops in such a way that it becomes more cost effective compared to our estimates, and it demonstrates the capability of meeting vehicle functional objectives, EPA expects that vehicle manufacturers may adopt that technology instead.

The Global Automakers commented that; "The decision to do so (create a new set of terms) unnecessarily complicated stakeholders' abilities to understand and track agency assumptions and their progression over time." EPA has decided to maintain this methodology in this Proposed Determination because we believe that this addresses comments previously received by stakeholders. For example, earlier in their comments on the Draft TAR, the Global Automakers point out that the actual penetration of DCTs in the 2015 MY fleet does not match the technology penetration projected by EPA in the FRM. EPA recognizes that the OMEGA model will always find the most cost effective solution. In the case of transmissions for the FRM, the OMEGA model applied a significant number of DCTs. Based on extensive meetings with manufacturers it became clear that the application of transmission technology was dependent on the market and functional objectives for a particular vehicle, with conventional automatics being the primary choice for large vehicles that tow, and DCTs being mostly applied to performance vehicles. The TRX methodology has provided a means by which EPA maintains the type of transmission technology found in the baseline fleet and be able to apply increasing effectiveness and the associated costs.

In their comments, the Alliance of Automobile Manufacturers (AAM) referred to this "binning" methodology of different types of transmissions (i.e., conventional ATs, CVTs, and

DCTs) into the TRX designations, claiming that the TRX designations "do not recognize unique efficiencies of different transmission technologies." The Alliance therefore recommends that EPA abandon the TRX designations and instead specifically identify each type of transmission. In this comment, the Alliance is joined by Ford Motor Company, which agrees that accounting for unique efficiencies of different transmissions is preferable. EPA agrees that conventional ATs, CVTs, and DCTs do represent unique technology packages. However, the potential effectiveness gains between TRX levels, while arising from different technology packages within each transmission type, will be very similar among the transmission types as noted in both the Draft TAR and earlier in this section of the TSD (see Figure 2.116). Furthermore, EPA believes that it is important to maintain customer choice, and that manufacturers will choose the appropriate transmission technology according to a range of customer requirements beyond CO2 emissions. The TRX designation implicitly assumes that manufacturers will be likely to maintain the transmission type already in the baseline fleet for a specific vehicle, according to their customer requirements. Manufacturers of course have the flexibility to switch transmission types, and gain any additional benefit in CO2 reduction accruing from changing transmission technology, but EPA does not consider this additional CO2 benefit in its analysis. Thus, EPA believes maintaining a TRX transmission designation is the best methodology for assessing technology cost and effectiveness while maintaining maximum manufacturer flexibility.

CVT transmissions in the 2015 MY baseline fleet have been characterized as TRX21 level transmissions. CVT transmissions were characterized as TRX11 in the Draft TAR. While EPA recognizes that some vehicles in the fleet have older CVTs that can be characterized as TRX11, EPA believes that it was best to characterize all CVTs as TRX21 for this Proposed Determination to be responsive to commenters and to be conservative. Thus, EPA recognizes the higher efficiency of current CVTs, but still allows them to improve. Most current CVT transmissions are 85 percent efficient and are expected to be 90-94 percent efficient by 2025. They are also expected to have their ratio span increase from the current 6-7.3 to between 8 and 8.5. Commenters questioned where these facts were obtained. These facts are based stakeholder meetings and oral presentations given by transmission suppliers at the last several CTI Transmission Symposiums in North America.

AAM commented, disagreeing with EPA's expectation for efficiency increased in CVTs. Toyota also commented that "Toyota believes that the transmission effectiveness becomes less due to the practical challenges." However, the Union of Concerned Scientists commented in support of EPA's assumptions for CVTs, pointing to the clear benefits to CVTs as an enabling technology. EPA has updated its estimate of CVT effectiveness within the TRX transmission structure for this Proposed Determination, and believes that it is conservative given the current and future efficiency and gear spread of CVTs.

2.3.4.2.2 *Effectiveness Values for TRX11 and TRX21*

The effectiveness associated with TRX11 is based on the GM 6T40 six-speed transmission from the 2013 Malibu benchmarking study. A comment received from AAM questioned the TRX11 effectiveness, but provided no further information or analysis. Consequently, EPA stands behind its documented analysis.

The effectiveness of TRX21 is based on the 845RE eight-speed transmission (a ZF licensed FCA clone) from the 2014 Dodge Ram benchmarking study.[587] Additional losses of 2 percent were added to the transmission to account for the differential, which was integral to the 6T40, and other spin losses found in front wheel drive transmissions. AAM commented that packaging difficulties in front wheel drive transmissions tend to increase spin and churning losses. EPA believes that the additional 2 percent losses assumed over the measured 845RE losses account take these losses into account. In addition, in more advanced FWD transmissions, manufacturers have tended to move clutches and other components out of the oil to further reduce churning losses. EPA has opted to maintain the additional 2 percent losses, even for transmissions with HEG2 (i.e., TRX22 transmissions).

A comment from Ford Motor Company stated that industry progress on transmission efficiency should be appropriately quantified in the baseline fleet. As outlined in the assumptions above, EPA believes that all manufacturers have incorporated some level of torque converter lockup improvements and gearbox efficiency improvements into transmissions with six speeds and above (i.e., TRX11 and TRX21 transmissions). Furthermore, EPA believes that the 6T40 is reasonably representative of current six-speed transmissions in the fleet, and that the 845RE (which is of more recent vintage than the 6T40 and contains additional efficiency improvements) is reasonably representative of current eight-speed transmissions in the fleet. Consequently, EPA believes industry progress on transmission efficiency has been appropriately quantified, and stands behind its documented analysis.

Comments from AAM and Ford stated that EPA's estimated effectiveness differences between current six- and eight-speed transmissions were high. AAM provided an attachment entitled, "EPA ALPHA Samples Transmission Walk,"[588] authored by Ford, in support. The transmission walk suggests that a 6-speed to 8-speed HEG1 transmission upgrade would result in a 4.4 percent - 5.0 percent effectiveness increase, rather than the 8.6 percent to 9.0 percent calculated by Ford using ALPHA simulation runs.

However, the Ford document acknowledges a number of differences between their simulation methodology and EPA's simulation methodology:

1) The Ford simulation engine used a 2.0L EcoBoost engine, compared to EPA's naturally aspirated GDI engines.
2) The Ford simulation assumed the same lockup strategy between transmissions; EPA's did not.
3) The Ford simulation used transmission efficiency maps from a Ford 8F24/8F35; EPA used benchmarked 845RE (ZF 8HP45) transmission as detailed in the Draft TAR.
4) The Ford simulation assumed no engine displacement reduction when the transmission is upgraded; EPA applied a "performance neutral" engine downsizing strategy.

As described in the Draft TAR (specifically in Table 5.77 of the Draft TAR), EPA expects that effectiveness percentages reported for transmissions paired with unimproved engines would be reduced when the same transmission is paired with a more advanced engine. Thus, Ford's technology walk using an EcoBoost engine would be expected to deliver a lower effectiveness than a comparable tech walks using the naturally aspirated engines modeled in ALPHA.

EPA also believes that, generally, eight-speed transmissions within the fleet are of a later vintage than six-speed transmissions within the fleet; and it is appropriate, when assigning effectiveness, to account for the entire package of transmission technology changes between a typical six- and eight- speed transmission. Thus, EPA uses representative transmissions, such as the six-speed 6T40 and the eight-speed 8HP45, in modeling, with the understanding that transmission efficiency, torque converter efficiency, and TC lockup strategy are different between the two. This assumption is reflected by the fact that the additional incremental effectiveness incorporated into HEG2 is reduced when applied to eight-speed transmissions, which are already assumed to contain some efficiency improvements in addition to the added gear ratios and spread.

Consistent with the FRM and recommendation by the National Academy of Science[589], the EPA analysis compares the technologies on a consistent basis by maintaining constant vehicle performance. In the EPA analysis, engine displacement was appropriately resized to maintain a consistent acceleration performance across different technology packages. The Ford transmission walk explicitly maintained engine size, with no allowance for maintaining performance, arguing that engine displacement reduction results in "significant gradeability degradation." AAM and FCA support Ford's contention on gradeability, with FCA commenting that "if [top gear gradeability] is too low, every time a driver encounters a small hill or wants to accelerate from a steady speed on a level road, the transmission would have to downshift. This is very annoying and leads to customer complaints."

EPA disagrees with this assessment. Both Ford and AAM define a gradeability metric of maintaining top gear at 75 mph while climbing a given grade. While this may have been an appropriate gradeability metric for vehicles containing vintage four-speed transmissions, EPA does not believe this metric is appropriate for advanced eight-speed transmissions, where downshifts are less noticeable to the driver. Moreover, in EPA testing, the FCA-built Dodge Charger downshifted significantly during the relatively gentle accelerations encountered over the HWFET. In addition, reviewers who drove the Jeep Cherokee[QQQ] commented that it does not maintain top gear on a flat road at 75 mph, implying that not all vehicles in production meet this metric.

[QQQ] http://www.caranddriver.com/reviews/2014-jeep-cherokee-24l-first-drive-review, http://www.tflcar.com/2015/02/is-the-2015-jeep-cherokee-limited-the-perfect-suv-first-impression/, http://www.fourwheeler.com/vehicle-reviews/1602-jeep-cherokee-trailhawk-why-did-it-win-2015-four-wheeler-of-the-year-award/

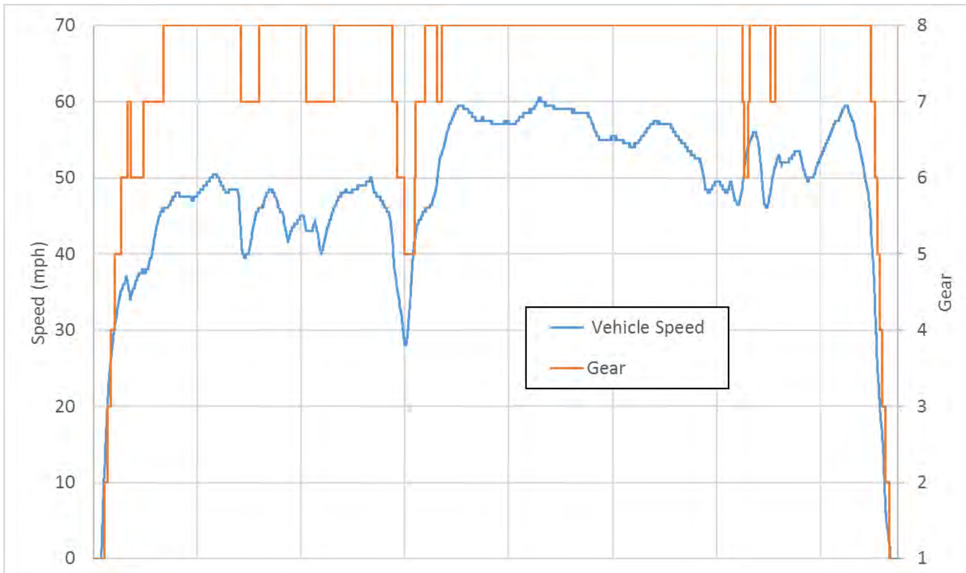


Figure 2.117 2015 Dodge Charger Gearing Changes over the HWFET

If top gear at 75 mph were used as a metric, EPA's preliminary analysis shows that advanced eight speed transmissions coupled with performance neutral engine sizing exhibit very little gradeability decrease, and with some engine technologies gradeability is increased over the baseline.

When applying the effect of these differences to the Ford simulation, the results are consistent with the EPA effectiveness measurements taken from ALPHA sample runs and cited by Ford in their transmission walk. EPA thus views the information in the transmission walk appendix as corroborative.

2.3.4.2.3 Effectiveness Values for TRX12 and TRX22

The effectiveness values for TRX12 and TRX22 contain additional technologies (HEG2) which, alone or in combination, can improve the efficiency of the gearbox.

EPA estimates of HEG2 effectiveness in eight-speed transmissions are based on modeling studies conducted by EPA and published in a 2016 paper referenced in the Draft TAR.[590] This paper outlines potential steps to improve transmission effectiveness, including increasing gear spread, reducing drag torque, reducing oil pump losses, reducing creep torque, implementing earlier torque converter lockup, and reducing engine size to maintain performance neutrality.

These specific advanced transmission technologies were assessed and reported on by transmission supplier ZF, who applied some of the technologies to their new 8-speed transmission (the 8HP50) and modeled the effect of others.[591] Results from the EPA simulations of these technologies (reported in the 2016 paper referenced) were close to, but somewhat lower than, the ZF estimates, so that the effectiveness numbers used by EPA for HEG2 in the Draft TAR analysis represent a conservative analysis compared to what transmission manufacturer ZF estimates can be achieved.

The expectation is that a transmission mapped to TRX11 can be improved to a level that would bring the transmission effectiveness to the efficiency level of the TRX22 (with effectiveness based on the ZF 8 speed with HEG level 2). Table 2.85 shows the effectiveness progression from a TRX11 level transmission to the TRX22 level transmission using the 2013 Malibu engine as modeled in ALPHA.

Table 2.85 TRX11 to TRX 22 Effectiveness Progression

	TRX11 to TRX12	TRX12 to TRX21	TRX21-TRX22
Range (all vehicle types)	3.4% - 3.5%	2.6% - 6.7%	3.6% - 4.4%

The aggregation of effectiveness values represents the best data available to EPA for the Proposed Determination analysis. EPA believes that these effectiveness values are appropriate since it allows an average of approximately 11 percent improvement in effectiveness from TRX11 to a TRX22. An 11 percent improvement in effectiveness is achievable given that most transmissions can gain 6-11 percent from efficiency improvements alone, and designs for increased gear counts and wider ratio spans from 8-10 are expected.

In comparison, AAM commented that "manufacturers expect that moving from TRX11 to TRX22 will deliver effectiveness improvements in that range of 1 percent-2 percent." Although AAM provided no data to support this comment, they did provide the Ford transmission walk referenced above, which provided an industry estimate that moving from TRX11 to TRX21 would deliver an effectiveness improvement of 4.4 percent to 5.0 percent. This is inconsistent with AAM's statement that advancing farther to TRX22 will provide a total benefit of at most 2 percent.

AAM also commented on what they consider to be marginal improvements due to HEG2 (i.e., the additional effectiveness gain from TRX21 to TRX22), offering in support of their comment information that FCA realized a CO_2 benefit of approximately 0.8 percent unadjusted combined FE when implementing friction reduction and hydraulic system upgrades to their eight-speed transmission.

AAM acknowledges that the modifications completed by FCA constituted only a portion of the HEG2 benefits expected by EPA given that certain additional improvements (notably a change in gear ratios) was not undertaken. In fact, HEG2 does include a basket of technologies that can be implemented individually or in combination by manufacturers; EPA does not expect all HEG2 technologies to be implemented simultaneously. FCA chose to implement a portion of the HEG2 technologies, and the benefit of approximately 0.8 percent is a representative proportion of the effectiveness projected by EPA when moving from transmission level TRX21 to TRX22. The 0.8 percent effectiveness realized by FCA for the technologies implemented is slightly lower than the values estimated by transmission supplier ZF in their published work, [592] but are consistent with EPA's implementation of HEG2 in the LPM.

2.3.4.2.4 *<u>Technology Applicability and Costs</u>*

For future vehicles, it was assumed that the costs for transitioning from one technology level (TRX11-TRX22) to another level is the same for each transmission type (AT, AMT, DCT, and CVT). The costs used are based on AT transmissions which make up over 70.8 percent of transmissions in today's fleet. The costs used in this analysis are equivalent to those intended for use in the Draft TAR, updated to 2015 dollars. Note that, subsequent to the Draft TAR, EPA found a minor error in its transmission costs whereby the indirect costs were slightly overstated. The costs presented below correct that error with the result that total costs in MY2025 for TRX21 are roughly $20 lower and TRX22 roughly $40 lower in this analysis than in the Draft TAR.

Transmission technology costs are presented in Table 2.86.

Table 2.86 Costs for Transmission Improvements for all Vehicles (dollar values in 2015$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
TRX11	DMC	$40	23	$36	$36	$35	$35	$34	$34	$33	$33	$33
TRX12	DMC	$260	23	$235	$232	$228	$225	$222	$219	$217	$214	$212
TRX21	DMC	$176	23	$159	$157	$155	$152	$150	$148	$147	$145	$143
TRX22	DMC	$396	23	$359	$353	$348	$343	$338	$334	$330	$326	$323
TRX11	IC	Low2	2018	$10	$10	$8	$8	$8	$8	$8	$8	$8
TRX12	IC	Low2	2018	$63	$63	$50	$50	$50	$50	$50	$50	$50
TRX21	IC	Low2	2024	$42	$42	$42	$42	$42	$42	$42	$42	$34
TRX22	IC	Low2	2024	$95	$95	$95	$95	$95	$95	$95	$95	$76
TRX11	TC			$46	$45	$43	$42	$42	$41	$41	$41	$40
TRX12	TC			$298	$294	$278	$275	$272	$269	$267	$264	$262
TRX21	TC			$202	$199	$197	$195	$193	$191	$189	$187	$177
TRX22	TC			$454	$448	$443	$438	$433	$429	$425	$421	$399

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

As a comparison to how the Draft TAR transmission, or TRX, costs presented above would compare to the transmission costs EPA used in the FRM, see the table below. To construct this table, EPA has added various FRM transmission technologies (updated to 2013$) together on a year-over-year basis and presented them along with the conceptual intent behind the new TRX structure discussed above. Note that the FRM costs were presented in 2010$ and, importantly, EPA revised the FRM transmission costs in 2013 due to FEV-generated updates to the tear down costs used in the 2012 FRM.[593] The FRM costs presented in the table below reflect the updates made to the FRM costs by FEV. We present the updated values rather than the actual FRM values since the updated values, if they were being used in this TSD analysis, are the values we would have used. As shown in Table 2.87, the TRX system projects high costs for each individual transmission type which is more conservative. Despite EPA projecting higher transmission technology costs than the 2012 FRM, and having similar transmission technology penetrations (and in some cases higher penetrations of more expensive technology), the overall cost of compliance for the 2022 to 2025 MY standards is similar.

Table 2.87 Comparison of Transmission Costs Using the 2012 FRM Methodology to Proposed Determination Costs for Transmissions (2015$)

Tech	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
6sp DCT-dry+ASL2+HEG1	TC	-$70	-$68	-$85	-$83	-$82	-$80	-$78	-$77	-$77
6sp DCT-wet+ASL2+HEG1	TC	-$30	-$29	-$40	-$39	-$38	-$37	-$36	-$36	-$36
6sp AT+ASL2+HEG1	TC	$25	$25	$24	$23	$23	$23	$23	$22	$21
TRX11	TC	$46	$45	$43	$42	$42	$41	$41	$41	$40
6sp DCT-dry+ASL2+HEG2	TC	$198	$196	$174	$172	$171	$169	$168	$167	$153

6sp DCT-wet+ASL2+HEG2	TC	$238	$235	$219	$217	$214	$212	$210	$208	$194
6sp AT+ASL2+HEG2	TC	$293	$288	$283	$279	$275	$272	$269	$266	$251
TRX12	TC	$298	$294	$278	$275	$272	$269	$267	$264	$262
8sp DCT-dry+ASL2+HEG1	TC	$92	$91	$90	$89	$88	$87	$86	$85	$79
8sp DCT-wet+ASL2+HEG1	TC	$190	$188	$186	$184	$182	$180	$178	$177	$163
8sp AT+ASL2+HEG1	TC	$124	$122	$114	$113	$112	$111	$109	$108	$106
TRX21	TC	$202	$199	$197	$195	$193	$191	$189	$187	$177
8sp DCT-dry+ASL2+HEG2	TC	$360	$354	$349	$344	$340	$336	$332	$328	$309
8sp DCT-wet+ASL2+HEG2	TC	$458	$451	$445	$439	$434	$429	$424	$420	$393
8sp AT+ASL2+HEG2	TC	$392	$386	$374	$369	$364	$360	$356	$352	$336
TRX22	TC	$454	$448	$443	$438	$433	$429	$425	$421	$399

2.3.4.3 Electrification: Data and Assumptions for this Assessment

As in the 2012 FRM and Draft TAR assessments, this Proposed Determination assessment relies on estimates of cost and effectiveness of each GHG-reducing technology in order to project its expected role in fleet compliance with the standards. Electrification technologies represent a particularly broad range of cost and effectiveness, ranging from relatively low-cost technologies offering incremental degrees of effectiveness, such as stop-start and mild hybrids, to higher-cost, highly effective technologies such as plug-in hybrids and pure electric vehicles.

In this analysis, the costs associated with electrification are divided into battery and non-battery costs. Chapter 2.2.4 of this TSD reviewed industry developments in battery and non-battery technology. As discussed in the Draft TAR, many of these developments have resulted in cost reductions for both battery and non-battery components as the industry has gained in experience and production scale. For this Proposed Determination assessment, EPA has reviewed its Draft TAR projections of cost and effectiveness for electrification technologies in the 2022-2025 time frame, and in many cases has made updates based on consideration of public comments received on the Draft TAR as well as updated information that became available since the publication of the Draft TAR.

2.3.4.3.1 Cost and Effectiveness for Non-hybrid Stop-Start

A complete assessment of the state of non-hybrid stop-start technology was presented in Chapter 2.2.4.4.1 of this TSD. To estimate cost and effectiveness of this technology for the Proposed Determination analysis, EPA has considered this information as well as public comments received on stop-start technology.

In general, public comments did not address the specific cost or effectiveness values for stop-start as used for the Draft TAR assessment (except in the context of off-cycle credit values, as discussed in Section B.3.4.1 of the Proposed Determination Appendix). A comment from Motor & Equipment Manufacturers Association (MEMA) did address the effectiveness of stop-start when implemented in a different manner from that assumed in the Draft TAR. The comment states, "Input from our members' modeling, development vehicle testing and analysis shows that correctly pairing two battery types together with a motor/generator can provide an additional 3 percent effectiveness beyond idle start-stop," and recommends that EPA include analysis of an optimized lead-acid and lithium ion dual energy storage system to represent the true benefit of such technology.

While EPA did acknowledge in the Draft TAR the possibility of pairing a battery with an ultra capacitor (as exemplified by the Mazda i-ELOOP technology), this technology was not analyzed more closely for effectiveness or cost, in favor of more standard configurations that are more typical of stop-start implementation. While stop-start can certainly be implemented in other ways that could potentially improve its cost or effectiveness, EPA does not have detailed information on cost or performance of dual-battery or capacitor-enhanced implementations that would allow including such variations in its analysis at this time.

No additional information was received to suggest that the Draft TAR cost or effectiveness values for stop-start should be revised. Therefore, EPA has chosen to maintain the Draft TAR effectiveness estimates for stop-start for use in this Proposed Determination analysis to reflect an effectiveness of 3.0 to 4.0 percent depending on vehicle class, as shown in Table 2.88.

Table 2.88 GHG Technology Effectiveness of Stop-Start

Technology	Technology Effectiveness [%]					
	LPW_LRL	MPW_LRL	HPW	LPW_HRL	MPW_HRL	Truck
12V Stop-Start	**3.0**	**3.5**	**4.0**	**3.6**	**3.7**	**3.7**

EPA is also retaining the costs for stop-start that were used in the Draft TAR, updated to 2015 dollars. The costs incremental to the baseline engine configuration for our different curb weight classes are shown below. Note that we have, in the past, estimated costs based on vehicle classes such as "small car" and "large MPV." As discussed in Section 2.1, we now estimate applicable costs more appropriately on curb weight class where 1 is the lightest class and 6 is the heaviest and is reserved for pickup trucks.

Table 2.89 Costs for Stop-Start for Different Curb Weight Classes (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	$317	25	$268	$253	$242	$233	$226	$219	$214	$209	$205
2	DMC	$317	25	$268	$253	$242	$233	$226	$219	$214	$209	$205
3	DMC	$360	25	$303	$287	$275	$265	$256	$249	$242	$237	$232
4	DMC	$360	25	$303	$287	$275	$265	$256	$249	$242	$237	$232
5	DMC	$360	25	$303	$287	$275	$265	$256	$249	$242	$237	$232
6	DMC	$395	25	$333	$315	$301	$290	$281	$273	$266	$260	$254
1	IC	Med2	2018	$121	$120	$90	$89	$89	$89	$89	$89	$88
2	IC	Med2	2018	$121	$120	$90	$89	$89	$89	$89	$89	$88
3	IC	Med2	2018	$137	$136	$102	$101	$101	$101	$101	$100	$100
4	IC	Med2	2018	$137	$136	$102	$101	$101	$101	$101	$100	$100
5	IC	Med2	2018	$137	$136	$102	$101	$101	$101	$101	$100	$100
6	IC	Med2	2018	$150	$149	$111	$111	$111	$111	$110	$110	$110
1	TC			$388	$374	$332	$323	$315	$308	$303	$298	$293
2	TC			$388	$374	$332	$323	$315	$308	$303	$298	$293
3	TC			$440	$423	$376	$366	$357	$350	$343	$337	$332
4	TC			$440	$423	$376	$366	$357	$350	$343	$337	$332
5	TC			$440	$423	$376	$366	$357	$350	$343	$337	$332

6	TC			$483	$464	$413	$401	$392	$383	$376	$370	$364

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.3.2 Cost and Effectiveness for Mild Hybrids

A complete assessment of this technology as performed for the Draft TAR and Proposed Determination was presented in Chapter 2.2.4.4.2 of this TSD. To estimate cost and effectiveness of this technology for the Proposed Determination analysis, EPA has considered this information as well as public comments received on the topic of mild hybrids.

Comments from Motor & Equipment Manufacturers Association (MEMA) recommended that EPA "more closely evaluate the potential for 48V systems in its analysis as an enabling technology that can leverage efficiencies in other vehicle systems or can provide other flexibilities." As an example, the comment noted that "electrically heated catalysts (EHCs) can be more efficiently powered by 48V systems to electrically light off the after treatment catalyst faster than possible when heated solely by exhaust gases." Another example was "thermodynamic hybridization through the use of e-boosting systems or electric supercharging." In a similar vein, the International Council on Clean Transportation (ICCT) commented, "We note that the TAR adds analyses of 48V hybrid systems, but we recommend that the agencies investigate the synergies between 48V hybrids and e-boost systems." Comments received from A123 Systems also listed a number of synergies and opportunities for increased efficiency that are enabled by a 48V system.

EPA acknowledges that ancillary advantages and synergies can accompany adoption of 48V systems, including such effects as faster and smoother engine start, greater opportunity for e-boost, and higher levels of power for electrical accessories. Although these advantages have potential to provide real value to consumers and can assist manufacturers with offering an integrated and compelling overall package, the EPA technology assessment methodology does not at this time include the capability to quantify the value of such ancillary benefits in a way that could be factored in to our projections of the cost effectiveness or market penetration of 48V technology.

Several commenters noted the decline in projected penetration of mild hybrids as compared to the FRM analysis. For example, American Council for an Energy-Efficient Economy (ACEEE) commented: "the penetration of mild hybrids in the agencies' 2025 compliance scenarios has declined from the levels found in the FRM … In the FRM, the compliance scenario included 26 percent penetration of mild hybrids in 2025, at a cost of $1553–1642. Yet, in the TAR, EPA finds only 18.3 percent mild hybrids (table 12.33), despite a revised cost projection of $806 (p. 5-302)."

In the EPA compliance projections presented in the Draft TAR, the projected market penetration of a given technology is primarily an outcome of the assumptions for cost and effectiveness that are supplied to OMEGA. The difference in projected penetration of mild hybrids between the 2012 FRM and Draft TAR is a result of the combined effect of many revisions and updates to technology assumptions throughout the analysis, including not only the addition of 48V systems to the Draft TAR analysis, but also changes in the cost and effectiveness assumptions for other technologies that compete with mild hybridization in the OMEGA model for inclusion in the projected compliant fleet. The reduced projected penetration of mild hybrids is therefore an outcome of the fleet compliance analysis as a whole and is not the result of any assumption about its potential to enter the market.

Regarding battery costs projected for the 48V system modeled in the Draft TAR analysis, A123 commented, "we find the total battery costs for 48V mild hybrid systems contained in Table 5.124 … to be overstated in the near term and more accurate near the end of the forecasted period," and attributed this to assumed learning curves for this technology as applied in the EPA analysis. The comment concluded that "this ultimately means that adoption of 48V mild hybrids in the near term would be more cost-effective in reducing GHG emissions (and improving fuel economy) than the DTAR projects."

Although the comment provides a reasoned discussion of the cost reduction potential from learning for 48V batteries, EPA has not chosen to modify its application of learning to this technology, because we continue to believe that the relatively low current penetration of 48V systems in the U.S. and worldwide continues to lend significant uncertainty to the proper learning rate that should be assumed. Lacking detailed and transparent data on this issue, and because battery cost is only part of total system cost, EPA believes that any modification of the applied learning rate that could be supported by a qualitative argument is unlikely to result in a sufficiently large change in projected system cost to strongly affect projected near-term penetration rates for this technology.

With regard to 48V costs, the Alliance commented that EPA's direct manufacturing costs for 48V BISG are too low, stating, "As is the case for many fuel efficiency technologies, mild hybrids do not simply 'bolt on' to provide reductions; they affect nearly every system on a vehicle which makes the true cost much greater than just the direct manufacturing cost price of the motor, belt, and larger battery." The comment goes on to list a number of technical concerns relating to performance, which were also briefly related further to other factors such as efficiency in comments by FCA. While EPA acknowledges that integrating new technology with an existing vehicle model to, as the comment suggests, "go from the baseline configuration to a 48V system," may carry additional costs for modifications and integration with the baseline system, it is also likely that over the long term, as 48V is integrated more deeply into the architecture of a manufacturer's product line, the impact of most if not all integration costs should be minimized. Technology cost inputs for the Draft TAR and Proposed Determination analyses are meant to reflect a fully developed technology implementation in the 2022-2025 time frame, at a time when manufacturers will have had opportunity to realize much of the potential benefit of design integration. As noted in comments by A123, ICCT, and MEMA, a 48V architecture can also enable efficiencies and improved performance in other vehicle systems, which brings substantial value of its own. In particular, as accessories continue to follow the recent trend of demanding an increasing amount of power (in many cases, to add features that customers demand), the availability of a 48V architecture provides this power more easily at potentially reduced cost. For example, electrical components such as conductors and motors may require less material and perform more efficiently at lower currents than required by a 12V system. EPA believes that the potential value of such efficiencies and synergies are as relevant as the initial integration costs, and that manufacturers are likely to find ways to realize that value as it becomes available.

Broadly, the Alliance questioned the agencies' assumptions for effectiveness, cost, and market penetration, while referring to differences in how this technology was represented by the agencies in their respective analyses. EPA notes that estimates of cost and effectiveness that are developed independently can ordinarily be expected to vary depending on the underlying assumptions, methodology, and data on which they are based. The cost and effectiveness figures used in EPA's analysis are supported by documented information and research, and on that basis EPA believes that they represent a fair and objective assessment of this technology.

With regard to cost and effectiveness of mild hybrids, Volkswagen commented, "Our own internal prognosis [for effectiveness] is at about 60 percent of EPA's estimates. Even in the 2020 time frame we assume the costs for 48V battery and system will still be almost twice as high as EPA's estimates." While these differences are noted, it is also well understood that estimates of cost and effectiveness from different sources have the potential to vary significantly depending on the underlying assumptions, methodology, and data on which they are based. Because no data was provided by VW to support the statement, the comment does not provide sufficient information to fully evaluate its basis and thereby perform an effective comparison to the figures EPA has developed from its own documented information and research.

EPA has considered the comments received on mild hybrid technology, and reviewed the availability of additional information on this technology, and believes that the Draft TAR cost and effectiveness values for mild hybrids remain applicable for the Proposed Determination analysis.

For this Proposed Determination analysis, as in the Draft TAR, EPA continues to assume a BISG configuration including a 12 kW electric machine and estimates a GHG effectiveness of 7.0 to 9.5 percent as shown in Table 2.90.

Table 2.90 GHG Technology Effectiveness of Mild Hybrids

Technology	Technology Effectiveness [%]					
	LPW_LRL	MPW_LRL	HPW	LPW_HRL	MPW_HRL	Truck
12-15 kW BISG 48-120V Mild Hybrid	**9.5**	**9.3**	**9.2**	**8.7**	**8.8**	**7.0**

EPA has also updated the battery costs for mild hybrids to 2015$ and these costs are reported in Table 2.125 of this TSD. Non- battery costs for mild hybrids have also been updated to 2015$ and are reported in Table 2.94. Full system costs are reported in Table 2.132.

2.3.4.3.3 Cost and Effectiveness for Strong Hybrids

A complete assessment of the state of strong hybrid technology was presented in Chapter 2.2.4.4.3 of this TSD. To estimate cost and effectiveness of this technology for the Proposed Determination analysis, EPA has considered this information as well as public comments received on the topic of strong hybrids.

For the Draft TAR, EPA calculated overall strong hybrid effectiveness by comparing the non-hybrid variants from the same vehicle manufacturers. For example, the 2015 2.5L I4 engine non-hybrid Camry was used to estimate the overall effectiveness of 2015 2.5L Camry hybrid. The use of a PFI Atkinson Cycle engine, improved aerodynamics, and reduced tire rolling resistance technology effectiveness were applied within the Lumped Parameter Model (LPM) to better estimate the overall system effectiveness of strong hybrid electrification since the Camry Hybrid vehicle package includes these differences in addition to the power-split HEV system. Two-cycle fuel economy (MPG) data over the city and highway drive cycles were used to estimate the relative effectiveness improvement of the hybrid electric vehicles. Hybrid technology effectiveness can then be estimated by subtracting the LPM/NRC-estimated effectiveness of non-hybrid technologies present on the vehicle from the total effectiveness.

The Draft TAR also noted that the effectiveness of input power-split hybrids and P2 parallel hybrids appear to be converging, citing as one example the fuel economy achieved with the 2017 Hyundai Ioniq P2 hybrid with a highly hybrid-optimized 6 speed DCT transmission.

Comments from The Alliance, and repeated by Ford, were concerned with the decision to model strong hybrids with the same cost and effectiveness without regard to specific architecture (P2 or power split). The Alliance commented, "the architectures of these two technologies are sufficiently different to warrant separate assessments," and recommended that EPA "develop separate cost and effectiveness projections for power-split and P2 hybrids."

While it might be ideal to model cost and effectiveness separately for all types of strong hybrid systems, the baseline vehicle fleet currently includes several types of strong hybrids (with more to be released in the near future), all with similar effectiveness. In conducting technology assessments and seeking to identify cost effective paths for compliance, EPA is primarily concerned with representing technologies in terms of performance without promoting specific architectures or configurations. For the FRM, Draft TAR, and Proposed Determination, a representative strong hybrid system was needed for modeling purposes, and EPA chose the P2 strong hybrid because the component parts were straightforward to perform a cost teardown, scaling of the system was straightforward, the technology can be applied to towing-capable vehicles, and the production effectiveness values are similar to other strong hybrids in the baseline fleet. This choice is not meant to suggest that EPA endorses the P2 architecture over any other, or believes that it is equally suitable for every potential application, but was simply the most efficient path to place a strong hybrid in the OMEGA analysis. As mentioned in the Draft TAR, the general public literature suggests that the costs and effectiveness of many of these strong hybrid architectures appear to be converging and in many cases are sufficiently close to bring into question the value of maintaining separate characterizations for each.

Toyota also commented, "Toyota does not agree with [the Draft TAR statement that the P2 hybrid architecture is lower cost than PS or power split], as the P2 hybrid method is not always lower in cost as compared to power-split method … in PS configuration, the motor also serves as a transmission, eliminating the need for a transmission. As a result, the PS configuration would not necessarily be higher in cost." This comment appears to further illustrate that there remain differences of opinion concerning the merits of each architecture, and that it can be difficult to make firm conclusions about the differences between P2 and PS architectures. Again, EPA chose the P2 configuration as a modeling construct for the reasons outlined above.

Toyota also pointed out, "In its assessment of the effectiveness of input power-split hybrids and P2 parallel hybrids as getting closer, per the recent 2017 Hyundai Ioniq P2 hybrid announcement, the Draft TAR states that the combined fuel economy of this vehicle is expected to be about 53 mpg, which is comparable to the 52 mpg fuel economy of the 2016 GEN4 Toyota Prius hybrid. However, this is incorrect as Eco grade model has a fuel economy rating of 56mpg." EPA acknowledges the correction, but also notes that in November 2016, Hyundai publicly announced that the Ioniq had been certified to achieve 58 mpg combined,[594] which would continue to be comparable to the 56 mpg figure.

Volkswagen agreed with EPA's effectiveness estimates for strong hybrids, but stated that they "estimate costs twice as high as EPA's estimates." Again, as discussed with respect to VW's comments on mild hybrids, the comment did not provide data to support the statement or allow it to be evaluated for comparability to the estimates that EPA has developed from its own documented information and research, including vehicle simulation and teardown analysis.

EPA has considered the comments that were submitted on strong hybrid technology, and has reviewed the availability of additional information on this technology. EPA believes that the Draft TAR cost and effectiveness values for strong hybrids remain applicable for the Proposed Determination analysis. EPA estimates the effectiveness for strong hybrid technology as shown in Table 2.91.

Table 2.91 GHG Technology Effectiveness of Strong Hybrids

Technology	Technology Effectiveness [%]					
	LPW_LRL	MPW_LRL	HPW	LPW_HRL	MPW_HRL	Truck
Strong Hybrid	19.0	20.1	19.9	18.8	19.1	17.7

For this Proposed Determination analysis, EPA has updated the battery costs for strong hybrids, as described in Chapter 2.3.4.3.7.2 and reported in Table 2.126. Non-battery costs have been retained for this analysis and updated to 2015$, and are reported in Table 2.95.

2.3.4.3.4 *Cost and Effectiveness for Plug-in Hybrids*

A complete assessment of the state of plug-in hybrid electric vehicle (PHEV) technology was presented in Chapter 2.2.4.4.4 of this TSD. To estimate cost and effectiveness of this technology for the Proposed Determination analysis, EPA has considered this information as well as public comments received on the topic of PHEVs.

As discussed in the Draft TAR, plug-in hybrid electric vehicles utilize two sources of energy, electricity and liquid fuel, which are accounted for differently according to the effectiveness accounting methods established in the 2012 FRM. The overall GHG effectiveness potential of PHEVs depends on many factors, the most important being the energy storage capacity designed into the battery pack, and the vehicle's ability to provide all electric range to the operator. Section 3.4.3.6.4 of the 2012 TSD detailed the method by which EPA estimates PHEV effectiveness. This method estimates effectiveness based on the SAE J1711 utility factor calculation, the AER, and the vehicle class. By this method, the assumed effectiveness for a PHEV20 would be approximately 58 percent GHG reduction for a midsize car and approximately 47 percent GHG reduction for a large truck.

The 2012 FRM established an incentive multiplier for compliance purposes for PHEVs sold in MYs 2017 through 2021. This multiplier approach means that each PHEV would count as more than one vehicle in the manufacturer's compliance calculation. The multiplier value for PHEVs starts at 1.6 in MY2017 and phases down to a value of 1.3 in MY2021. There is no PHEV multiplier for MYs 2022-2025.

The 2012 FRM also set the tailpipe compliance value for the electricity portion of PHEV energy usage to 0 g/mi for MYs 2017-2021, with no limit on the quantity of vehicles eligible for 0 g/mi tailpipe emissions accounting. For MYs 2022-2025, 0 g/mi will only be allowed up to a per-company cumulative sales cap: 1) 600,000 vehicles for companies that sell 300,000 BEV/PHEV/FCVs in MYs 2019-2021; 2) 200,000 vehicles for all other manufacturers. For sales above these thresholds, manufacturers will be required to account for the net upstream GHG emissions for the electric portion of operation, using accounting methodologies set out in the FRM.

For compliance modeling, as discussed in Section C.1 of the Proposed Determination Appendix, this Proposed Determination analysis includes an accounting for upstream emissions associated with all electricity consumption for all manufacturers in all MY2025 OMEGA runs.[RRR]

Few public comments on the Draft TAR concerned PHEVs specifically, as distinguished from broader issues common to plug-in vehicles in general, which are addressed in their respective applicable chapters of this TSD. One comment was received from Manufacturers of Emission Controls Association (MECA) related to so-called "puff losses" that release emissions on cap removal from the pressurized fuel tank that is commonly associated with PHEVs. EPA is aware that the unique design of a PHEV, which includes not only an electrical powertrain but also a gasoline power plant that is used on demand, poses certain difficulties with regard to cold-start, evaporative, and cap removal emissions. While these emissions are potentially of concern, puff losses are not directly considered in either the Draft TAR or Proposed Determination analyses because these analyses are primarily concerned with the 2022-2025 GHG standards rather than criteria emissions.

As with other plug-in vehicles, costs for PHEVs are separated into battery and non-battery costs, which are discussed in their respective sections. For further discussion of these costs and applicable updates for this Proposed Determination analysis, please refer to Chapters 2.3.4.3.6 and 2.3.4.3.7 of this TSD. Battery costs used by OMEGA for PHEVs in this analysis are reported in Table 2.127 and Table 2.128 of this TSD. Non-battery costs are reported in Table 2.96 and Table 2.97. Full system costs for PHEVs are reported in Table 2.134 and Table 2.135.

2.3.4.3.5 *Cost and Effectiveness for Battery Electric Vehicles*

A complete assessment of the state of battery electric vehicle (BEV) technology was presented in Chapter 2.2.4.4.5 of this TSD. To estimate cost and effectiveness of this technology for the Proposed Determination analysis, EPA has considered this information as well as public comments received on the topic of BEVs.

EPA received a number of public comments relating to the general topic of BEVs. Additional comments that were identified as relating more specifically to battery and non-battery costs as they apply to BEVs are discussed separately in Chapters 2.3.4.3.6 and 2.3.4.3.7.

Many of the comments received on BEV technology were related to projected costs in the Draft TAR. Regarding projected costs of BEVs as compared to conventional vehicles, Tesla

[RRR] Note that, for emissions inventory modeling, an accounting for upstream emissions associated with electricity consumption is and always has been done, but this is different than the accounting done for compliance modeling.

Motors commented: "The TAR assumes that BEV technology is the most complex for automakers to develop and proliferate, regardless of range, and applies the highest cost assumptions for BEV development through 2024. According to the TAR, for every $1.00 that automakers spend on direct manufacturing costs for a BEV, they will spend another $0.77 on all other costs such as R&D, corporate overhead and selling expenses. This assumption results in a projected loss of 18 percent on BEV product lines and gives the impression that automakers cannot profitably pursue BEV technology as a viable compliance option. However, both Tesla and independent equity analyst projections show that this is not the case. Consensus estimates forecast that Tesla will achieve annual corporate-level profitability in 2017."

While the Draft TAR analysis does not specifically project profitability, it is true that at the present time, manufacturers are experiencing generally higher costs to produce a BEV than to produce a conventional vehicle, and this differing cost basis exerts pressure on the relative profitability of BEVs. While BEVs and conventional vehicles differ in complexity (with BEVs commonly described as having fewer parts, simpler construction, and lower maintenance costs), it is also true that many components specific to BEVs have not reached production volumes similar to those of conventional vehicles. The concept of cost parity between BEVs and conventional vehicles, and when it might be achieved, is an important construct in the consideration of the potential for BEVs to become a large percentage of the fleet. In general, cost parity means that the cost of ICE components that would be present in a conventional vehicle is at least equal to the cost of electrified components that would replace them. It may also include consideration of cost of ownership, vehicle utility, and other factors. The cost of battery and non-battery components is obviously a major factor to cost parity.

EPA has taken considerable effort to maintain and validate the method by which it projects battery costs, which is made possible in part by the availability of ANL BatPaC and its flexibility to model widely differing scenarios and inputs. The ability to similarly address non-battery costs is made more difficult by the lack of a similar model. It should also be noted that the profitability case for a manufacturer dedicated solely to BEVs may be different from the experience of a manufacturer that is dividing its attention between electrified and conventional vehicles. While the current cost projections that are possible using EPA's current tool set may not represent the full potential for optimization and cost reduction that a dedicated manufacturer may experience, it may by contrast better represent less optimized scenarios that are likely to continue to be applicable in the near term.

Regarding projected penetrations of BEVs in the future fleet, Faraday Future commented: "We recognize that the Draft TAR acknowledges the trend of increasing range for BEVs and mentions the introduction of both the Tesla Model 3 and the Chevy Bolt in Section 5.2.4.3.5. However, the Draft TAR includes no analysis of the likely groundbreaking impact of these models on the BEV market in the United States. Instead, the Draft TAR continues to apply assumptions from the OMEGA and Volpe models that the increased range of BEVs will not be a cost-effective compliance path for manufacturers. The actual actions of the auto industry in moving to the production of BEVs shows that these assumptions are overly conservative."

EPA acknowledges the possibility that the BEV market may grow rapidly in the coming years despite relatively low market penetration levels at the present. The penetration rates projected in the Draft TAR are not directly selected but are primarily the result of the OMEGA model and its selection of available technologies on the basis of cost effectiveness. The model does not at this time have the ability to represent additional market penetration that may occur for other reasons, such as relative utility, brand appeal, performance, or other factors.

Regarding EPA's choice of BEV200 as the longest-range BEV in the analysis, Volkswagen stated: "by offering only 200mi BEVs, the gap between conventional and electrified cars will remain and will fall short of fulfilling consumer expectations. To meet consumer expectations regarding range, larger batteries would be required which ultimately results in higher costs versus costs projected by the agencies. Therefore, we suggest including BEVs with larger battery sizes to take these aspects into consideration."

EPA acknowledges that BEV200 represents a shorter range than seen in some current BEVs that have well over 200 miles range. Recently this longer-range market has been dominated by Tesla vehicles, which have constituted a premium, performance-oriented segment, but is soon poised to add consumer-segment vehicles (such as the Chevy Bolt and Tesla Model 3). Tesla has previously suggested that the Model 3 will have about 215 miles of range, which is not far from the BEV200 assumption. The Chevy Bolt, now certified at 238 miles, is farther from BEV200, but it remains to be seen whether this will in fact cause the segment to coalesce at a similar or longer range figure over the long term. For example, Tesla may choose to increase the range of the Model 3 to compete with the Bolt, or similarly could choose to compete on price by offering a slightly shorter range while taking advantage of its strong brand image. It remains unclear whether the market will coalesce around longer range vehicles at a higher cost, or settle at a lower range with a lower cost. As previously discussed in Chapter 2.2.4 (Electrification: State of Technology), announcements of other near-term future BEVs do not appear to be consistently targeting a range beyond 200 miles. Ford has announced intent to introduce a BEV, described as having an approximately 200-mile range;[595] reports suggest that Toyota is planning to produce BEVs with a range of "more than 300 km" (or 186 mi);[596,597] and it continues to appear that Nissan is likely to be targeting a 200-mile real-world range with a future version of the Leaf.[598] EPA has therefore chosen to retain BEV200 for this analysis.

Regarding the argument that EPA should consider a more appropriate way to determine the average range characteristics of the fleet for use in development of the reference and/or baseline fleet (see comments from the Alliance of Automobile Manufacturers at pp 69-70), EPA and CARB believe that using a sales-weighted average approach to determining range when estimating the number of ZEV program vehicles to inject into the OMEGA analysis fleet is the most appropriate and fair way to make the estimation. Short of that, we would need product plans from manufacturers which we would, presumably, not be allowed to release publicly. Without direct input from manufacturers, in the form of product plans, the approach taken seems most appropriate and conservative. We have followed the same approach in the Proposed Determination analysis (see Chapter 1.2 of this TSD).

Comments were also received on the subject of incentives for BEVs. As discussed in the Draft TAR, the 2012 FRM established temporary incentives for PEVs, including an incentive multiplier for MYs 2017 through 2021, and a 0 g/mi accounting for tailpipe emissions for MYs 2017-2025 (subject to sales thresholds for MYs 2022-2025). Public comments received on these incentives and multipliers are addressed in Section B.3.4.2 of the Proposed Determination Appendix.

The effectiveness of BEVs is obviously very high when their tailpipe emissions are counted as 0 g/mi, regardless of the driving range or efficiency of the vehicle itself. In this Proposed

Determination analysis, BEVs (on average) are assigned a lower effectiveness than in the Draft TAR due to the addition of an accounting for upstream emissions in the compliance projections. Our prior analyses, including the Draft TAR analysis, did not consider PEV upstream emissions in compliance modeling. [SSS] Given the growing rate of PEV sales, it now appears that some manufacturers are likely to exceed the sales levels beyond which net upstream emissions would have to be considered in their compliance determination, while other manufacturers likely will not. Therefore, we now include upstream emissions for BEV operation and the electricity portion of PHEV operation in the compliance determinations for all manufacturers by MY2025. Because we wish to be conservative in our estimates, we have chosen to model all MY2025 PEVs as including upstream emissions even though it is not expected that all manufacturers will have exceeded the sale levels by then.

As with other plug-in vehicles, costs for BEVs are separated into battery and non-battery costs. EPA has updated battery costs for BEVs as described in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs). Discussion of non-battery costs applicable to BEVs may be found in Chapter 2.3.4.3.6 (Cost of Non-Battery Components of xEVs). As previously mentioned, some public comments that were related more specifically to BEV battery and non-battery costs may be found in these chapters.

Battery costs for BEVs used by the OMEGA model are reported in Table 2.129 through Table 2.131 of this TSD. Non-battery costs are reported in Table 2.98 through Table 2.100, and full system costs (including charging installation and equipment) are reported in Table 2.136 through Table 2.138.

2.3.4.3.6 Cost of Non-Battery Components for xEVs

For this Proposed Determination assessment, EPA has considered public comments received on non-battery components for xEVs, as well as reviewed the availability of additional information regarding this topic.

EPA received several comments that related to the non-battery costs used in the Draft TAR GHG Assessment.

Regarding general plug-in vehicle costs, Ford Motor Company stated, "In general, the cost associated with plug-in electric technologies appears to be conservative." While not addressed specifically to non-battery costs, non-battery costs are a part of the overall cost structure that this comment appears to address.

Comments from Tesla Motors were more direct on this topic. Tesla commented that "Tesla's non-battery component costs for Model 3 are lower by double-digit percentages in every category versus the 2020 U.S. DRIVE figures considered in the TAR." With respect to this specific comment, EPA wishes to clarify that, although the Draft TAR briefly reviewed the 2020 U.S. DRIVE cost targets for motors and power electronics, these targets were not ultimately used

[SSS] Note that, for emissions inventory modeling, an accounting for upstream emissions associated with electricity consumption is and always has been done, but this is different than the accounting done for compliance modeling.

by EPA in its cost projections; only the estimates for non-battery specific power were based on U.S. DRIVE targets.

However, the comment does suggest that Tesla Motors believes that the Draft TAR non-battery costs, regardless of their source, are significantly higher than projected by Tesla Motors for the upcoming Model 3. Tesla stated, "Tesla's non-battery powertrain component costs for Model 3 are dramatically lower than the costs the Agencies are considering for 2025 BEV production … From the 2008 Roadster to the Model 3, we have realized cost reductions of more than 60 percent on non-battery components. These savings are due in part to improvements in the volumetric and gravimetric profile of the components, which have led to substantial reductions in direct manufacturing costs per unit. We see significant room for further cost reductions between Model 3 launch in 2017 and the regulatory timeline covered in the TAR (2022 – 2025)."

While these statements are encouraging, more information would be needed to effectively evaluate the EPA non-battery cost projections with respect to Tesla's experience.

The Tesla comments also stated, "We are very concerned by the fact that the costs presented in the TAR related to Battery Electric Vehicles (BEVs) are significantly overstated and do not reflect a realistic assessment of the future of this technology. If the Agencies update their BEV assumptions to incorporate both current and planned cost reductions, the TAR will clearly show that Zero Emission Vehicles can profitably represent a much higher portion of the automotive industry's compliance with the 2022 – 2025 standards … The electric powertrain costs presented in the TAR are largely anchored to figures shared by incumbent automakers who have made minimal efforts to deploy compelling BEV programs and have not realized the cost benefits of high-volume manufacturing of electric powertrain components. The costs used by the Agencies to determine the future of these regulations should reflect what is possible if the automotive industry is sufficiently motivated to earnestly pursue mass-market BEV programs."

EPA agrees that costs for manufacturers that have aggressively pursued electrification are likely to be lower, at least in the near term, than costs experienced by others. If this is the case, EPA believes that an accurate accounting of electrification costs during the time frame of the rule should represent costs as they are likely to be experienced across the full spectrum of manufacturers, even those that may utilize PEVs as a relatively small portion of their compliance path, as EPA projects. In order to represent a fully optimized set of costs attainable by large-scale PEV manufacturers, EPA would require specific data, which the comment does not provide, that establishes the degree to which these costs are outperforming the costs developed for the Draft TAR and this Proposed Determination.

Comments from the International Council on Clean Transportation (ICCT) also described the projected BEV costs as too high. ICCT commented, "Overall the agencies appear to have overestimated electric vehicle costs in the TAR. The agencies have utilized state-of-the-art tools including the DOE BatPaC model on battery costs. However, somehow costs elsewhere in the agencies' calculations appear to have pushed up electric vehicles' incremental costs to still remain above $10,000 in the 2025 time frame. Based on our examination of detailed engineering cost files for the TAR, we see agency incremental technology costs for 100- and 200-mile BEVs of $11,000 to $14,000 in 2025. We believe the agencies have overestimated these incremental technology costs, as the ICCT's recent analysis for a similar C-class compact car are approximately $3,100 to $7,300, respectively, for the same BEV ranges."

Regarding both the Tesla and ICCT comments, EPA agrees that costs for battery and non-battery components are continuing on a downward trajectory. In order to quantify that trajectory, especially as it applies to highly optimized PEV manufacturers, EPA would need more information than the comments provide, such as detailed cost breakdowns and the assumptions that underlie them, in order to evaluate the comparability of the estimates and potentially use such information to improve our non-battery cost estimates. It should also be noted that the full system cost estimates for PEVs found in the Draft TAR include the cost of charger equipment and installation labor, which are commonly not included in cost estimates for xEVs and so may make the Draft TAR estimates appear higher than other sources to which they might be compared.

With regard to production volumes assumed in the Draft TAR analysis, Global Automakers commented: "It is important to recognize that at … low volumes, manufacturers cannot obtain economies of scale. In the 2012 FRM, the agencies considered a volume of 450,000 units necessary to achieve full economies of scale. In its 2015 study, the NRC noted that the technology penetration levels projected by the agencies did not reach that level, and that no one manufacturer would reach that level. In the TAR, the agencies respond that economies of scale can be obtained at levels as low as 60,000, and put forward a number of other arguments on battery costs. Nonetheless, it cannot be denied that at current sales levels of electric-drive vehicles of less than one percent (1 percent) of the market (i.e., less than 17,000 vehicles), manufacturers are not close to volumes that could provide economies of scale. Unless demand for those vehicles increases dramatically, economies of scale will remain out of reach."

While the cited arguments in the Draft TAR were directed primarily at battery costs, the comment appears to also extend to the role of economies of scale in reducing non-battery costs. Again, it is clear that some manufacturers will not achieve as large volumes as others, and therefore not experience the same economies of scale as may be experienced by dedicated BEV manufacturers during this time frame. The structure of the EPA analysis would make it very difficult to assign different cost structures to different manufacturers, and would require additional data specific to each manufacturer's product and research plans in order to develop or validate related assumptions. Some commenters have strongly suggested that the EPA non-battery cost estimates are very conservative, which if true, would tend to benefit the applicability of the projected costs to manufacturers with smaller production volumes.

Assuming smaller volumes for the 2022 to 2025 time frame would also presuppose that volumes cannot and will not increase dramatically over the next six to nine years. While this is one possibility, another possibility is that innovation, regulatory forces, growth in consumer knowledge of BEV technology, and continuing evolution in consumer expectations and preferences will combine to increase production volumes of electrified vehicles, as several other commenters have suggested.

Nextgen Climate America commented, "The Draft TAR overlooks several opportunities to lay that foundation [for global GHG reduction targets] by relying on a set of unnecessarily conservative assumptions about the capabilities and benefits of electric vehicles. There is ample evidence that electric vehicles can offer greater benefits than they are currently assigned under the scenarios considered in the draft TAR. Using more realistic estimates of electric vehicle costs, capacity and benefits will better align Phase II of the light duty fuel economy and emissions standards with expected market behavior as well as set a better foundation for the U.S. to achieve critical climate goals."

EPA acknowledges that an accurate assessment of BEV costs is important to accurately projecting the full potential for this technology to achieve the market penetrations necessary to achieve large reductions in GHG emissions. EPA has accordingly continued to pursue improvements in its modeling of battery costs, a dominant factor in BEV costs, for this Proposed Determination analysis. Due to the design of the OMEGA model to select GHG-reducing technologies for inclusion in potential manufacturer compliance paths primarily on the basis of cost effectiveness and not on other potentially relevant (but difficult to quantify) factors such as benefits of electric drive, even a greatly cost-reduced assessment of longer-range BEVs such as BEV200 may continue to have difficulty competing with other more conventional technologies for inclusion in these projections.

As discussed in the Draft TAR, CARB has commissioned a study on non-battery costs for strong HEVs and PHEVs in support of its own ongoing programs.[599] At the time, EPA anticipated that this study, although it was designed for the specific needs of CARB, might also serve as an additional source of non-battery cost findings that could be readily adapted to the EPA non-battery cost analysis. Because it is concerned with the potential for future cost reductions, it was expected that this would have the effect of downwardly revising our projected non-battery costs if the findings could be effectively incorporated. This study is now underway but is not complete, and the adaptability of the findings to the EPA cost model remains uncertain. EPA believes that the current non-battery cost estimates as applied to the Draft TAR and this Proposed Determination continue to represent a reasonably conservative assessment within the context of the modeling problem as a whole.

The Draft TAR also mentioned that EPA has studied the possibility of adopting US DRIVE cost targets for motors and power electronics, based on information gained through stakeholder meetings that suggests that some OEMs may already be meeting or exceeding some of these targets, or are on track to do so within the time frame of the rule. EPA ultimately decided not to do so, largely due to uncertainty as to the basis of the target figures as representing direct manufacturing costs as assumed for other technologies in the analysis.

Home charging equipment is another aspect of non-battery cost. In both the Draft TAR and Proposed Determination analyses, all PEVs are assumed to be associated with a home charging installation that includes a significant cost for installation labor, plus an additional cost for Level 1 or Level 2 charging hardware, depending on the vehicle type. PHEV20 and some PHEV40 vehicles are assigned a blend of Level 1 and Level 2 charging, while all BEVs and larger PHEVs are assigned 100 percent Level 2 charging. Specific costs used by OMEGA are shown in Table 2.101 through Table 2.104. Public comments received on home charging, as well as public charging infrastructure, are discussed in more detail in Chapter 2.2.4.4.5 (Battery Electric Vehicles).

Also as discussed in the Draft TAR, the 2015 NAS report correctly noted that raw material costs for propulsion motors tends to be a stronger function of torque output than of power output, and recommended that the agencies scale motor costs on a torque basis. In the Draft TAR, EPA acknowledged the technical basis of this recommendation, and pointed out that practical considerations make it difficult to do so while remaining compatible with other aspects of the analysis that require motors to be characterized by power output. Accurately converting between a torque basis and a power basis would require a greater amount of information to be specified about the individual propulsion systems and drivelines of each of the modeled PHEVs, possibly limiting the applicability of the analysis to a narrower range of configurations than intended. Further, through additional research and through stakeholder meetings with OEMs, EPA has found that it is not unusual to encounter motor cost projections or targets being expressed in terms of power, such as dollars per kilowatt. The US DRIVE cost targets for electric motors published by the Department of Energy are also expressed in dollars per kilowatt. Finally, the cost of the power electronics that accompany a propulsion motor system are closely related to the power specification of the propulsion motor, and are also commonly projected or targeted as a function of power. For these reasons, as in the Draft TAR analysis, EPA continues to scale motor and power electronics costs in terms of power rather than torque.

No additional comment was received that includes sufficiently specific data with which the non-battery costs used in the Draft TAR could be effectively adjusted, either to represent larger or smaller volumes, or more or less optimized development programs (as mentioned by some of the comments). EPA is therefore continuing to use the Draft TAR cost assumptions for non-battery components for this Proposed Determination analysis. Although the underlying cost basis for non-battery components remains unchanged, non-battery costs have been slightly affected by differences in motor sizing resulting from updates to the battery sizing methodology, as described in Chapter 2.3.4.3.7.1. The exception to this is that, for 48V MHEV non-battery components, we continue to use the Draft TAR estimates, updated to 2015 dollars.

All applicable non-battery costs are presented in the tables below, first in terms of cost curves as were presented in the Draft TAR, and then for each curb weight class at various mass reduction levels. Note that we have, in the past, estimated costs based on vehicle classes such as "small car" and "large MPV." As discussed in Chapter 2.1, we now estimate applicable costs more appropriately on curb weight class where 1 is the lightest class and 6 is the heaviest and is reserved for pickup trucks.

Table 2.92 Linear Regressions of Strong & Plug-in Hybrid Non-Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2012 (2015$)

Curb Weight Class	Strong HEV	PHEV20	PHEV40
1	-$283x+$1,847	$46x+$2,183	$89x+$2,667
2	-$375x+$2,002	$61x+$2,403	$120x+$3,045
3	-$417x+$2,055	$68x+$2,486	$133x+$3,195
4	-$533x+$2,144	$88x+$2,653	-$260x+$3,585
5	-$646x+$2,366	$107x+$2,968	$209x+$4,061
6	-$682x+$2,377	n/a	n/a

Note: “x” in the equations represents the net weight reduction as a percentage.

Table 2.93 Linear Regressions of Battery Electric Non-Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2016 (2015$)

Curb Weight Class	BEV75	BEV100	BEV200
1	$110x+-$149	$110x+-$149	$105x+-$147
2	$148x+$280	$147x+$280	$142x+$281
3	$165x+-$492	$164x+-$492	$158x+-$490
4	$214x+$13	$212x+$14	$205x+$14
5	$260x+$589	$257x+$589	$574x+$581
6	n/a	n/a	n/a

Note: “x” in the equations represents the net weight reduction as a percentage.

Table 2.94 Costs for MHEV48V Non-Battery Items (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$452	23	$410	$403	$397	$392	$387	$382	$377	$373	$369
All	IC	Med2	2018	$173	$173	$129	$129	$129	$129	$129	$129	$128
All	TC			$583	$576	$527	$521	$516	$511	$506	$501	$497

Note:
DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.95 Costs for Strong Hybrid Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	6	DMC	$1,830	23	$1,657	$1,631	$1,607	$1,585	$1,564	$1,544	$1,526	$1,509	$1,492
1	15	11	DMC	$1,816	23	$1,644	$1,618	$1,594	$1,572	$1,552	$1,532	$1,514	$1,497	$1,481
1	20	16	DMC	$1,802	23	$1,631	$1,606	$1,582	$1,560	$1,540	$1,520	$1,502	$1,485	$1,469
2	10	6	DMC	$1,980	23	$1,793	$1,764	$1,738	$1,714	$1,692	$1,671	$1,651	$1,632	$1,614
2	15	11	DMC	$1,961	23	$1,776	$1,748	$1,722	$1,698	$1,676	$1,655	$1,635	$1,617	$1,599
2	20	16	DMC	$1,942	23	$1,759	$1,731	$1,705	$1,682	$1,660	$1,639	$1,619	$1,601	$1,584
3	10	5	DMC	$2,034	23	$1,842	$1,813	$1,786	$1,762	$1,738	$1,717	$1,696	$1,677	$1,659
3	15	10	DMC	$2,014	23	$1,823	$1,795	$1,768	$1,744	$1,721	$1,699	$1,679	$1,660	$1,642
3	20	15	DMC	$1,993	23	$1,804	$1,776	$1,750	$1,726	$1,703	$1,682	$1,662	$1,643	$1,625
4	10	6	DMC	$2,112	23	$1,912	$1,882	$1,854	$1,828	$1,804	$1,782	$1,761	$1,741	$1,722
4	15	11	DMC	$2,085	23	$1,888	$1,858	$1,831	$1,805	$1,782	$1,759	$1,738	$1,719	$1,700
4	20	16	DMC	$2,058	23	$1,864	$1,835	$1,807	$1,782	$1,759	$1,737	$1,716	$1,697	$1,678
5	10	6	DMC	$2,328	23	$2,108	$2,074	$2,044	$2,015	$1,989	$1,964	$1,941	$1,919	$1,898
5	15	11	DMC	$2,295	23	$2,078	$2,046	$2,016	$1,988	$1,961	$1,937	$1,914	$1,892	$1,872
5	20	16	DMC	$2,263	23	$2,049	$2,017	$1,987	$1,960	$1,934	$1,910	$1,887	$1,866	$1,845
6	10	6	DMC	$2,336	23	$2,115	$2,082	$2,051	$2,023	$1,996	$1,971	$1,948	$1,926	$1,905
6	15	11	DMC	$2,302	23	$2,084	$2,052	$2,021	$1,993	$1,967	$1,943	$1,919	$1,898	$1,877
6	20	16	DMC	$2,268	23	$2,054	$2,021	$1,992	$1,964	$1,938	$1,914	$1,891	$1,870	$1,849
1	10	6	IC	High1	2018	$1,020	$1,019	$625	$624	$624	$623	$622	$622	$621
1	15	11	IC	High1	2018	$1,012	$1,011	$620	$619	$619	$618	$618	$617	$617
1	20	16	IC	High1	2018	$1,004	$1,003	$615	$615	$614	$613	$613	$612	$612
2	10	6	IC	High1	2018	$1,104	$1,102	$676	$675	$675	$674	$673	$673	$672
2	15	11	IC	High1	2018	$1,093	$1,091	$670	$669	$668	$668	$667	$666	$666
2	20	16	IC	High1	2018	$1,083	$1,081	$663	$663	$662	$661	$661	$660	$659
3	10	5	IC	High1	2018	$1,134	$1,132	$695	$694	$693	$693	$692	$691	$691
3	15	10	IC	High1	2018	$1,123	$1,121	$688	$687	$686	$685	$685	$684	$684
3	20	15	IC	High1	2018	$1,111	$1,109	$681	$680	$679	$678	$678	$677	$677
4	10	6	IC	High1	2018	$1,177	$1,175	$721	$720	$720	$719	$718	$718	$717
4	15	11	IC	High1	2018	$1,162	$1,160	$712	$711	$711	$710	$709	$709	$708
4	20	16	IC	High1	2018	$1,148	$1,146	$703	$702	$701	$701	$700	$699	$699
5	10	6	IC	High1	2018	$1,298	$1,295	$795	$794	$793	$792	$792	$791	$790
5	15	11	IC	High1	2018	$1,280	$1,278	$784	$783	$782	$781	$781	$780	$779
5	20	16	IC	High1	2018	$1,262	$1,260	$773	$772	$771	$770	$770	$769	$768
6	10	6	IC	High1	2018	$1,302	$1,300	$798	$797	$796	$795	$795	$794	$793
6	15	11	IC	High1	2018	$1,283	$1,281	$786	$785	$784	$784	$783	$782	$782
6	20	16	IC	High1	2018	$1,264	$1,262	$775	$774	$773	$772	$771	$771	$770
1	10	6	TC			$2,677	$2,649	$2,232	$2,209	$2,187	$2,167	$2,148	$2,130	$2,114
1	15	11	TC			$2,656	$2,629	$2,215	$2,192	$2,170	$2,150	$2,132	$2,114	$2,097
1	20	16	TC			$2,636	$2,608	$2,197	$2,175	$2,153	$2,134	$2,115	$2,097	$2,081
2	10	6	TC			$2,896	$2,866	$2,415	$2,390	$2,366	$2,345	$2,324	$2,305	$2,286
2	15	11	TC			$2,869	$2,839	$2,392	$2,367	$2,344	$2,322	$2,302	$2,283	$2,265
2	20	16	TC			$2,841	$2,812	$2,369	$2,344	$2,321	$2,300	$2,280	$2,261	$2,243
3	10	5	TC			$2,976	$2,945	$2,481	$2,456	$2,432	$2,409	$2,388	$2,368	$2,350

3	15	10	TC			$2,946	$2,915	$2,456	$2,430	$2,407	$2,385	$2,364	$2,344	$2,326
3	20	15	TC			$2,915	$2,885	$2,430	$2,405	$2,382	$2,360	$2,339	$2,320	$2,302
4	10	6	TC			$3,089	$3,057	$2,575	$2,549	$2,524	$2,501	$2,479	$2,458	$2,439
4	15	11	TC			$3,050	$3,019	$2,543	$2,517	$2,492	$2,469	$2,448	$2,427	$2,408
4	20	16	TC			$3,011	$2,980	$2,510	$2,485	$2,460	$2,438	$2,416	$2,396	$2,377
5	10	6	TC			$3,405	$3,370	$2,839	$2,810	$2,782	$2,757	$2,732	$2,710	$2,688
5	15	11	TC			$3,358	$3,323	$2,799	$2,771	$2,744	$2,718	$2,695	$2,672	$2,651
5	20	16	TC			$3,311	$3,276	$2,760	$2,732	$2,705	$2,680	$2,657	$2,635	$2,614
6	10	6	TC			$3,418	$3,382	$2,849	$2,820	$2,792	$2,767	$2,742	$2,720	$2,698
6	15	11	TC			$3,368	$3,333	$2,808	$2,779	$2,752	$2,726	$2,702	$2,680	$2,659
6	20	16	TC			$3,318	$3,284	$2,766	$2,737	$2,711	$2,686	$2,662	$2,640	$2,619

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.96 Costs for 20 Mile Plug-in Hybrid Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	15	6	DMC	$2,185	23	$1,979	$1,948	$1,919	$1,892	$1,867	$1,844	$1,822	$1,801	$1,782
1	20	11	DMC	$2,188	23	$1,981	$1,950	$1,921	$1,894	$1,869	$1,846	$1,824	$1,803	$1,784
2	15	6	DMC	$2,407	23	$2,180	$2,145	$2,114	$2,084	$2,057	$2,031	$2,007	$1,984	$1,963
2	20	11	DMC	$2,410	23	$2,182	$2,148	$2,116	$2,087	$2,059	$2,034	$2,010	$1,987	$1,965
3	15	6	DMC	$2,490	23	$2,254	$2,219	$2,186	$2,156	$2,127	$2,101	$2,076	$2,052	$2,030
3	20	11	DMC	$2,493	23	$2,257	$2,222	$2,189	$2,159	$2,130	$2,104	$2,079	$2,055	$2,033
4	15	6	DMC	$2,658	23	$2,407	$2,369	$2,334	$2,302	$2,272	$2,243	$2,217	$2,191	$2,168
4	20	11	DMC	$2,663	23	$2,411	$2,373	$2,338	$2,306	$2,275	$2,247	$2,220	$2,195	$2,171
5	15	6	DMC	$2,975	23	$2,694	$2,651	$2,612	$2,576	$2,542	$2,510	$2,480	$2,452	$2,426
5	20	11	DMC	$2,980	23	$2,698	$2,656	$2,617	$2,581	$2,547	$2,515	$2,485	$2,457	$2,430
6	15	6	DMC	$2,996	23	$2,713	$2,670	$2,631	$2,594	$2,560	$2,528	$2,498	$2,470	$2,443
6	20	11	DMC	$3,002	23	$2,718	$2,675	$2,636	$2,599	$2,565	$2,533	$2,503	$2,475	$2,448
1	15	6	IC	High1	2018	$1,218	$1,216	$746	$745	$745	$744	$743	$743	$742
1	20	11	IC	High1	2018	$1,220	$1,218	$747	$746	$745	$745	$744	$743	$743
2	15	6	IC	High1	2018	$1,342	$1,340	$822	$821	$820	$819	$819	$818	$817
2	20	11	IC	High1	2018	$1,344	$1,341	$823	$822	$821	$821	$820	$819	$818
3	15	6	IC	High1	2018	$1,388	$1,386	$850	$849	$848	$848	$847	$846	$845
3	20	11	IC	High1	2018	$1,390	$1,388	$851	$850	$850	$849	$848	$847	$846
4	15	6	IC	High1	2018	$1,482	$1,480	$908	$907	$906	$905	$904	$903	$903
4	20	11	IC	High1	2018	$1,484	$1,482	$909	$908	$907	$906	$906	$905	$904
5	15	6	IC	High1	2018	$1,658	$1,656	$1,016	$1,015	$1,014	$1,013	$1,012	$1,011	$1,010
5	20	11	IC	High1	2018	$1,661	$1,659	$1,018	$1,017	$1,016	$1,015	$1,014	$1,013	$1,012
6	15	6	IC	High1	2018	$1,670	$1,668	$1,023	$1,022	$1,021	$1,020	$1,019	$1,018	$1,017
6	20	11	IC	High1	2018	$1,674	$1,671	$1,025	$1,024	$1,023	$1,022	$1,021	$1,020	$1,019
1	15	6	TC			$3,197	$3,164	$2,665	$2,638	$2,612	$2,588	$2,565	$2,544	$2,524
1	20	11	TC			$3,200	$3,167	$2,668	$2,640	$2,615	$2,591	$2,568	$2,547	$2,526
2	15	6	TC			$3,521	$3,485	$2,936	$2,905	$2,877	$2,851	$2,826	$2,802	$2,780
2	20	11	TC			$3,526	$3,489	$2,940	$2,909	$2,881	$2,854	$2,829	$2,806	$2,784
3	15	6	TC			$3,642	$3,605	$3,036	$3,005	$2,976	$2,948	$2,923	$2,898	$2,875
3	20	11	TC			$3,647	$3,609	$3,041	$3,009	$2,980	$2,952	$2,927	$2,902	$2,879
4	15	6	TC			$3,889	$3,849	$3,242	$3,209	$3,177	$3,148	$3,121	$3,095	$3,070
4	20	11	TC			$3,895	$3,855	$3,248	$3,214	$3,183	$3,153	$3,126	$3,100	$3,075
5	15	6	TC			$4,352	$4,307	$3,628	$3,591	$3,556	$3,523	$3,492	$3,463	$3,436
5	20	11	TC			$4,360	$4,315	$3,635	$3,597	$3,562	$3,529	$3,498	$3,469	$3,442
6	15	6	TC			$4,383	$4,338	$3,654	$3,617	$3,581	$3,548	$3,517	$3,488	$3,461
6	20	11	TC			$4,392	$4,346	$3,661	$3,623	$3,588	$3,555	$3,524	$3,495	$3,467

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.97 Costs for 40 Mile Plug-in Hybrid Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	7	DMC	$2,673	23	$2,420	$2,382	$2,347	$2,315	$2,284	$2,256	$2,229	$2,204	$2,180
2	20	6	DMC	$3,052	23	$2,763	$2,720	$2,680	$2,643	$2,608	$2,575	$2,545	$2,516	$2,489
3	20	5	DMC	$3,202	23	$2,899	$2,854	$2,812	$2,773	$2,736	$2,702	$2,670	$2,640	$2,611
4	20	5	DMC	$3,572	23	$3,234	$3,183	$3,136	$3,093	$3,052	$3,014	$2,978	$2,944	$2,913
5	20	7	DMC	$4,076	23	$3,691	$3,633	$3,579	$3,529	$3,483	$3,439	$3,399	$3,360	$3,324
6	20	6	DMC	$4,104	23	$3,716	$3,658	$3,604	$3,554	$3,507	$3,463	$3,422	$3,383	$3,347
1	20	7	IC	High1	2018	$1,490	$1,488	$913	$912	$911	$910	$909	$908	$908
2	20	6	IC	High1	2018	$1,701	$1,699	$1,042	$1,041	$1,040	$1,039	$1,038	$1,037	$1,036
3	20	5	IC	High1	2018	$1,785	$1,782	$1,094	$1,092	$1,091	$1,090	$1,089	$1,088	$1,087
4	20	5	IC	High1	2018	$1,991	$1,988	$1,220	$1,218	$1,217	$1,216	$1,215	$1,214	$1,213
5	20	7	IC	High1	2018	$2,272	$2,269	$1,392	$1,390	$1,389	$1,388	$1,386	$1,385	$1,384
6	20	6	IC	High1	2018	$2,288	$2,284	$1,402	$1,400	$1,399	$1,397	$1,396	$1,395	$1,393
1	20	7	TC			$3,911	$3,870	$3,260	$3,227	$3,195	$3,166	$3,138	$3,112	$3,087
2	20	6	TC			$4,465	$4,419	$3,722	$3,684	$3,648	$3,614	$3,583	$3,553	$3,525
3	20	5	TC			$4,684	$4,636	$3,905	$3,865	$3,827	$3,792	$3,759	$3,728	$3,698
4	20	5	TC			$5,225	$5,171	$4,356	$4,311	$4,269	$4,230	$4,193	$4,158	$4,125
5	20	7	TC			$5,963	$5,901	$4,971	$4,920	$4,872	$4,827	$4,785	$4,745	$4,708
6	20	6	TC			$6,004	$5,942	$5,006	$4,954	$4,906	$4,860	$4,818	$4,778	$4,740

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.98 Costs for 75 Mile BEV Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	DMC	-$138	28	-$135	-$132	-$129	-$127	-$125	-$123	-$121	-$119	-$118
1	15	15	DMC	-$132	28	-$129	-$126	-$124	-$122	-$120	-$118	-$116	-$114	-$113
1	20	20	DMC	-$127	28	-$124	-$121	-$119	-$117	-$115	-$113	-$111	-$110	-$108
2	10	10	DMC	$295	28	$288	$282	$277	$272	$267	$263	$259	$255	$252
2	15	15	DMC	$302	28	$295	$289	$283	$278	$274	$269	$265	$262	$258
2	20	20	DMC	$310	28	$303	$296	$290	$285	$280	$276	$272	$268	$265
3	10	10	DMC	-$476	28	-$465	-$455	-$446	-$438	-$431	-$424	-$418	-$412	-$406
3	15	15	DMC	-$467	28	-$456	-$447	-$438	-$430	-$423	-$416	-$410	-$405	-$399
3	20	20	DMC	-$459	28	-$448	-$439	-$430	-$423	-$416	-$409	-$403	-$397	-$392
4	10	10	DMC	$35	28	$34	$33	$33	$32	$32	$31	$31	$30	$30
4	15	15	DMC	$46	28	$45	$44	$43	$42	$41	$41	$40	$39	$39
4	20	20	DMC	$56	28	$55	$54	$53	$52	$51	$50	$49	$49	$48
5	10	10	DMC	$615	28	$601	$588	$576	$566	$557	$548	$540	$532	$525
5	15	15	DMC	$628	28	$613	$600	$589	$578	$568	$559	$551	$544	$536
5	20	20	DMC	$641	28	$626	$613	$601	$590	$580	$571	$563	$555	$547
6	10	10	DMC	-$635	28	-$620	-$607	-$595	-$584	-$575	-$566	-$557	-$549	-$542
6	15	15	DMC	-$621	28	-$606	-$594	-$582	-$572	-$562	-$553	-$545	-$538	-$530
6	20	20	DMC	-$607	28	-$593	-$581	-$569	-$559	-$550	-$541	-$533	-$526	-$519
1	10	10	IC	High2	2024	$106	$106	$105	$105	$105	$105	$105	$105	$67
1	15	15	IC	High2	2024	$102	$101	$101	$101	$101	$101	$101	$100	$65
1	20	20	IC	High2	2024	$97	$97	$97	$97	$97	$97	$96	$96	$62
2	10	10	IC	High2	2024	$227	$226	$226	$225	$225	$225	$224	$224	$144
2	15	15	IC	High2	2024	$232	$232	$231	$231	$231	$230	$230	$230	$148
2	20	20	IC	High2	2024	$238	$237	$237	$237	$236	$236	$236	$235	$152
3	10	10	IC	High2	2024	$365	$365	$364	$363	$363	$362	$362	$361	$233
3	15	15	IC	High2	2024	$359	$358	$358	$357	$357	$356	$356	$355	$229
3	20	20	IC	High2	2024	$353	$352	$351	$351	$350	$350	$349	$349	$225
4	10	10	IC	High2	2024	$27	$27	$27	$27	$27	$27	$27	$27	$17

4	15	15	IC	High2	2024	$35	$35	$35	$35	$35	$35	$35	$35	$22
4	20	20	IC	High2	2024	$43	$43	$43	$43	$43	$43	$43	$43	$28
5	10	10	IC	High2	2024	$472	$471	$471	$470	$469	$468	$468	$467	$301
5	15	15	IC	High2	2024	$482	$481	$480	$480	$479	$478	$478	$477	$307
5	20	20	IC	High2	2024	$492	$491	$490	$490	$489	$488	$488	$487	$314
6	10	10	IC	High2	2024	$488	$487	$486	$485	$484	$484	$483	$482	$311
6	15	15	IC	High2	2024	$477	$476	$475	$474	$474	$473	$472	$472	$304
6	20	20	IC	High2	2024	$466	$465	$465	$464	$463	$463	$462	$461	$297
1	10	10	TC			-$29	-$26	-$24	-$22	-$20	-$18	-$16	-$15	-$50
1	15	15	TC			-$28	-$25	-$23	-$21	-$19	-$17	-$15	-$14	-$48
1	20	20	TC			-$26	-$24	-$22	-$20	-$18	-$16	-$15	-$13	-$46
2	10	10	TC			$515	$508	$502	$497	$492	$488	$483	$480	$396
2	15	15	TC			$528	$521	$515	$509	$504	$500	$496	$492	$406
2	20	20	TC			$541	$534	$528	$522	$517	$512	$508	$504	$416
3	10	10	TC			-$99	-$90	-$82	-$74	-$68	-$61	-$56	-$50	-$174
3	15	15	TC			-$97	-$89	-$81	-$73	-$67	-$60	-$55	-$49	-$171
3	20	20	TC			-$96	-$87	-$79	-$72	-$65	-$59	-$54	-$49	-$168
4	10	10	TC			$61	$60	$59	$59	$58	$58	$57	$57	$47
4	15	15	TC			$80	$79	$78	$77	$76	$75	$75	$74	$61
4	20	20	TC			$98	$97	$96	$95	$94	$93	$92	$92	$76
5	10	10	TC			$1,073	$1,059	$1,047	$1,036	$1,026	$1,016	$1,008	$1,000	$826
5	15	15	TC			$1,095	$1,082	$1,069	$1,058	$1,047	$1,038	$1,029	$1,021	$844
5	20	20	TC			$1,118	$1,104	$1,091	$1,080	$1,069	$1,059	$1,050	$1,042	$861
6	10	10	TC			-$132	-$120	-$109	-$99	-$90	-$82	-$74	-$67	-$232
6	15	15	TC			-$129	-$118	-$107	-$97	-$88	-$80	-$73	-$66	-$227
6	20	20	TC			-$127	-$115	-$105	-$95	-$86	-$78	-$71	-$64	-$222

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.99 Costs for 100 Mile BEV Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	DMC	-$138	28	-$135	-$132	-$129	-$127	-$125	-$123	-$121	-$119	-$118
1	15	15	DMC	-$132	28	-$129	-$126	-$124	-$122	-$120	-$118	-$116	-$115	-$113
1	20	20	DMC	-$127	28	-$124	-$121	-$119	-$117	-$115	-$113	-$111	-$110	-$108
2	10	10	DMC	$295	28	$288	$282	$276	$272	$267	$263	$259	$255	$252
2	15	15	DMC	$302	28	$295	$289	$283	$278	$274	$269	$265	$262	$258
2	20	20	DMC	$310	28	$302	$296	$290	$285	$280	$276	$272	$268	$265
3	10	9	DMC	-$477	28	-$466	-$456	-$448	-$439	-$432	-$425	-$419	-$413	-$408
3	15	14	DMC	-$469	28	-$458	-$449	-$440	-$432	-$425	-$418	-$412	-$406	-$401
3	20	19	DMC	-$461	28	-$450	-$441	-$432	-$424	-$417	-$411	-$405	-$399	-$394
4	10	10	DMC	$35	28	$34	$33	$33	$32	$32	$31	$31	$30	$30
4	15	15	DMC	$45	28	$44	$43	$43	$42	$41	$40	$40	$39	$39
4	20	20	DMC	$56	28	$55	$54	$53	$52	$51	$50	$49	$49	$48
5	10	10	DMC	$615	28	$600	$588	$576	$566	$556	$548	$540	$532	$525
5	15	15	DMC	$627	28	$613	$600	$588	$578	$568	$559	$551	$543	$536
5	20	20	DMC	$640	28	$625	$612	$600	$590	$580	$571	$562	$554	$547
6	10	9	DMC	-$637	28	-$623	-$610	-$598	-$587	-$577	-$568	-$560	-$552	-$545
6	15	14	DMC	-$624	28	-$609	-$597	-$585	-$574	-$565	-$556	-$548	-$540	-$533
6	20	19	DMC	-$610	28	-$596	-$584	-$572	-$562	-$552	-$544	-$536	-$528	-$521
1	10	10	IC	High2	2024	$106	$106	$105	$105	$105	$105	$105	$105	$67
1	15	15	IC	High2	2024	$102	$101	$101	$101	$101	$101	$101	$101	$65
1	20	20	IC	High2	2024	$97	$97	$97	$97	$97	$97	$97	$96	$62
2	10	10	IC	High2	2024	$227	$226	$226	$225	$225	$225	$224	$224	$144
2	15	15	IC	High2	2024	$232	$232	$231	$231	$231	$230	$230	$230	$148
2	20	20	IC	High2	2024	$238	$237	$237	$237	$236	$236	$236	$235	$152
3	10	9	IC	High2	2024	$367	$366	$365	$365	$364	$364	$363	$363	$234
3	15	14	IC	High2	2024	$360	$360	$359	$358	$358	$357	$357	$357	$230
3	20	19	IC	High2	2024	$354	$353	$353	$352	$352	$351	$351	$350	$226

4	10	10	IC	High2	2024	$27	$27	$27	$27	$27	$27	$26	$26	$17
4	15	15	IC	High2	2024	$35	$35	$35	$35	$35	$35	$35	$35	$22
4	20	20	IC	High2	2024	$43	$43	$43	$43	$43	$43	$43	$43	$27
5	10	10	IC	High2	2024	$472	$471	$470	$470	$469	$468	$468	$467	$301
5	15	15	IC	High2	2024	$482	$481	$480	$479	$479	$478	$477	$477	$307
5	20	20	IC	High2	2024	$492	$491	$490	$489	$489	$488	$487	$487	$313
6	10	9	IC	High2	2024	$490	$489	$488	$487	$486	$486	$485	$485	$312
6	15	14	IC	High2	2024	$479	$478	$477	$477	$476	$475	$475	$474	$305
6	20	19	IC	High2	2024	$469	$468	$467	$466	$466	$465	$464	$464	$299
1	10	10	TC			-$29	-$26	-$24	-$22	-$20	-$18	-$16	-$15	-$50
1	15	15	TC			-$28	-$25	-$23	-$21	-$19	-$17	-$15	-$14	-$48
1	20	20	TC			-$26	-$24	-$22	-$20	-$18	-$16	-$15	-$13	-$46
2	10	10	TC			$515	$508	$502	$497	$492	$487	$483	$479	$396
2	15	15	TC			$527	$521	$515	$509	$504	$500	$495	$491	$406
2	20	20	TC			$540	$533	$527	$522	$517	$512	$507	$503	$416
3	10	9	TC			-$100	-$90	-$82	-$75	-$68	-$62	-$56	-$50	-$174
3	15	14	TC			-$98	-$89	-$81	-$73	-$67	-$61	-$55	-$50	-$171
3	20	19	TC			-$96	-$87	-$79	-$72	-$66	-$60	-$54	-$49	-$168
4	10	10	TC			$61	$60	$59	$59	$58	$58	$57	$57	$47
4	15	15	TC			$79	$78	$77	$77	$76	$75	$74	$74	$61
4	20	20	TC			$98	$97	$95	$94	$94	$93	$92	$91	$75
5	10	10	TC			$1,073	$1,059	$1,047	$1,036	$1,025	$1,016	$1,007	$999	$826
5	15	15	TC			$1,095	$1,081	$1,069	$1,057	$1,047	$1,037	$1,028	$1,020	$843
5	20	20	TC			$1,117	$1,103	$1,090	$1,079	$1,068	$1,059	$1,049	$1,041	$860
6	10	9	TC			-$133	-$121	-$110	-$100	-$91	-$82	-$75	-$67	-$233
6	15	14	TC			-$130	-$118	-$107	-$98	-$89	-$81	-$73	-$66	-$228
6	20	19	TC			-$127	-$116	-$105	-$96	-$87	-$79	-$71	-$65	-$223

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.100 Costs for 200 Mile BEV Non-Battery Items (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	13	DMC	-$133	28	-$130	-$128	-$125	-$123	-$121	-$119	-$117	-$116	-$114
2	20	14	DMC	$301	28	$294	$288	$282	$277	$273	$268	$264	$261	$257
3	20	13	DMC	-$470	28	-$459	-$449	-$440	-$433	-$425	-$419	-$412	-$407	-$401
4	20	14	DMC	$43	28	$42	$41	$40	$40	$39	$38	$38	$37	$37
5	20	14	DMC	$661	28	$646	$632	$620	$609	$598	$589	$580	$572	$565
6	20	13	DMC	-$627	28	-$612	-$599	-$588	-$577	-$568	-$559	-$550	-$543	-$536
1	20	13	IC	High2	2024	$103	$102	$102	$102	$102	$102	$102	$101	$65
2	20	14	IC	High2	2024	$231	$231	$231	$230	$230	$229	$229	$229	$147
3	20	13	IC	High2	2024	$361	$360	$360	$359	$358	$358	$357	$357	$230
4	20	14	IC	High2	2024	$33	$33	$33	$33	$33	$33	$33	$33	$21
5	20	14	IC	High2	2024	$508	$507	$506	$505	$504	$504	$503	$502	$324
6	20	13	IC	High2	2024	$482	$481	$480	$479	$478	$478	$477	$476	$307
1	20	13	TC			-$28	-$25	-$23	-$21	-$19	-$17	-$16	-$14	-$49
2	20	14	TC			$526	$519	$513	$507	$502	$498	$494	$490	$405
3	20	13	TC			-$98	-$89	-$81	-$74	-$67	-$61	-$55	-$50	-$171
4	20	14	TC			$75	$74	$73	$73	$72	$71	$71	$70	$58
5	20	14	TC			$1,154	$1,139	$1,126	$1,114	$1,103	$1,093	$1,083	$1,075	$888
6	20	13	TC			-$131	-$119	-$108	-$98	-$89	-$81	-$73	-$66	-$229

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.101 Costs for In-Home Charger Associated with 20 Mile Plug-in Hybrid (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$33	26	$54	$50	$48	$45	$43	$41	$40	$39	$37
All	IC	High1	2024	$20	$20	$20	$20	$19	$19	$19	$19	$12

All	TC			$74	$70	$67	$65	$63	$61	$59	$58	$49

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.102 Costs for In-Home Charger Associated with 40 Mile Plug-in Hybrid (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	DMC	$175	26	$282	$264	$250	$238	$227	$218	$210	$202
2	DMC	DMC	$203	26	$327	$307	$290	$276	$264	$253	$244	$235
3	DMC	DMC	$222	26	$358	$336	$317	$302	$288	$277	$266	$257
4	DMC	DMC	$222	26	$358	$336	$317	$302	$288	$277	$266	$257
5	DMC	DMC	$222	26	$358	$336	$317	$302	$288	$277	$266	$257
6	DMC	DMC	$222	26	$358	$336	$317	$302	$288	$277	$266	$257
1	IC	IC	High1	2024	$105	$104	$103	$102	$102	$101	$101	$100
2	IC	IC	High1	2024	$122	$121	$120	$119	$118	$118	$117	$116
3	IC	IC	High1	2024	$134	$132	$131	$130	$129	$128	$128	$127
4	IC	IC	High1	2024	$134	$132	$131	$130	$129	$128	$128	$127
5	IC	IC	High1	2024	$134	$132	$131	$130	$129	$128	$128	$127
6	IC	IC	High1	2024	$134	$132	$131	$130	$129	$128	$128	$127
1	TC	TC			$387	$368	$353	$340	$329	$319	$310	$303
2	TC	TC			$450	$428	$410	$395	$382	$371	$361	$351
3	TC	TC			$491	$468	$448	$432	$418	$405	$394	$384
4	TC	TC			$491	$468	$448	$432	$418	$405	$394	$384
5	TC	TC			$491	$468	$448	$432	$418	$405	$394	$384
6	TC	TC			$491	$468	$448	$432	$418	$405	$394	$384

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.103 Costs for In-Home Charger Associated with All BEVs (dollar values in 2015$)

Curb Weight Class & Range	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$222	26	$358	$336	$317	$302	$288	$277	$266	$257	$249
All	IC	High1	2024	$134	$132	$131	$130	$129	$128	$128	$127	$77
All	TC			$491	$468	$448	$432	$418	$405	$394	$384	$326

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.104 Costs for Labor Associated with All In-Home Chargers for Plug-in & BEV (dollar values in 2015$)

Curb Weight Class & Range	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$1,108	1	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108
All	IC	None	2024	$0	$0	$0	$0	$0	$0	$0	$0	$0
All	TC			$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108	$1,108

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.3.7 Cost of Batteries for xEVs

A significant portion of the cost of an electrified vehicle is represented by the cost of the battery. Battery costs have many drivers, and future cost projections derived by any methodology are subject to significant uncertainties. The choice of costing methodology is therefore an important consideration.

A core component of the EPA battery costing methodology is BatPaC,[600] a peer-reviewed battery costing model developed by Argonne National Laboratory (ANL). As described later in Section 2.3.4.3.7.3, the ANL BatPaC model employs a rigorous, bottom-up, bill-of-materials approach to battery cost analysis, and has undergone continual development and review since the 2012 FRM.

BatPaC requires numerous input assumptions, including battery energy capacity, battery output power, and many other assumptions describing the chemistry, construction, and other aspects of the battery. EPA determines battery energy capacity and output power by means of a battery sizing methodology that dynamically provides these inputs to BatPaC. Other inputs are informed by information gathered from relevant sources as reviewed in EPA's assessment of the state of battery related technologies presented in Chapter 2.2.4.5.

This section reviews how EPA developed the battery costing methodology used for the Draft TAR and this Proposed Determination, and how inputs to the battery sizing methodology and to BatPaC were updated for this Proposed Determination analysis. The Microsoft Excel workbooks that EPA used to determine battery sizing and perform ANL BatPaC calculations for this Proposed Determination are also available in the Docket.[601]

EPA considered public comments received on battery costs and related technologies, and has continued to assess technology developments that have occurred since completion of the Draft TAR. EPA has carefully considered these comments and developments in updating the battery-related assumptions and inputs for this Proposed Determination analysis. Some comments relating to the cost projections or methodologies in general are examined here, while other comments relating to specific inputs are addressed later in the discussion in their respective contexts.

Comments by Ford and Volkswagen appear to generally support the battery cost projections of the Draft TAR. Ford commented, "In general, the cost associated with plug-in electric technologies appears to be conservative" (subject to further understanding of the basis of the agencies' assumptions). Volkswagen stated, "Volkswagen agrees with the projected costs for a 200mi BEV for MY2025," in the context of a discussion of range assumptions.

The Alliance of Automobile Manufacturers (AAM) commented, "Some initial feedback for the Agencies is to ensure costs assumptions are not just for energy cells, and to present what size the system is relative to cost, as there are economies of scale and large battery system costs can be different from those for mild or even strong hybrids used by the automotive industry."

As discussed later in this Chapter, the EPA battery sizing methodology does in fact account for the size and power requirements of the system by using ANL BatPaC to design each cell. Power and energy requirements are inputs to BatPaC, and result in design of the constituent cells to accommodate the power and energy required. Battery packs for energy-oriented systems, such as BEVs, are composed of energy cells optimized for energy storage, while power-oriented system such as for HEVs are composed of power-optimized cells.

AAM also commented, "Further, it may be more appropriate for the Agencies to use different cost metrics for mild hybrids reflecting different usage and requirements for these systems." Again, both mild and strong HEV packs are designed to provide the power and energy requirements that are specifically assigned to each modeled vehicle.

With respect to learning rates and battery costs, AAM also commented, "while there may be some learning for battery manufacturers, there are also many tradeoffs with this technology that will require extensive research and development (R&D) which must be considered especially for any new and yet to be discovered chemistries, cooling methods, or additional safety concepts." EPA notes that, to account for indirect costs associated with electrification, such as research and development costs, EPA applies indirect cost multipliers that are added to the direct manufacturing costs for battery and non-battery components.

Comments from Faraday Future provided an example of battery cost per kWh that had not been specifically reviewed in the Draft TAR. Faraday stated that a report issued by the International Energy Agency (IEA)[602,603,604] in 2015 reported costs as "below $250 per kWh," which Faraday described as "in the lower range of costs surveyed by the Agencies." Also, Faraday characterized the report as projecting that "the trend of falling battery costs makes it realistic to predict that battery costs will reach $125 per kWh -- the level the Department of Energy has estimated is needed for cost competitiveness with conventional vehicles -- by 2022 … This latest information on battery costs should be added to the Agencies’ analysis for the Midterm Evaluation."

EPA acknowledges this additional source. Of course, cost per kWh can vary significantly depending on battery capacity and power output, meaning that an estimated cost per kWh is most meaningful in the context of a specific application. Also, it is important to know whether the cost is being quoted as a direct manufacturing cost, or a retail price, or on some other basis. Assuming that these costs are meant to apply to longer-range BEVs (such as BEV200) and are quoted as direct manufacturing costs, the estimate of $125 per kWh in 2022 is not far from the corresponding projections in the Draft TAR.

Tesla Motors commented, "Improvements in battery cell design and scale manufacturing at the Gigafactory will enable Tesla to achieve cell-level and pack-level costs by 2020 that are far below the 2025 TAR assumptions." EPA understands that the Gigafactory is to be a very large scale plant that is designed to achieve significant economies of scale, and notes that the EPA battery analysis is also based upon a very large scale manufacturing scenario for which similar economies of scale would also be expected to apply. The EPA cost projections are based on outputs from ANL BatPaC, which ANL describes as representing a mature, large scale plant operating in 2020. EPA provides BatPaC with inputs describing a production scale of 450,000 packs per year and applies the output cost projections to the year 2025, generating estimates for earlier years by reverse application of learning curves. Although Tesla may be expecting their battery costs to be lower than this methodology projects, this observation does not provide enough information to assess the source of the difference or the comparability of Tesla's projections to the figures generated for the EPA analysis. While qualitative examples of specific manufacturers' experiences with reducing battery costs are informative and welcome, for EPA to potentially account for such information in its projection of future battery costs, the information would ultimately have to be translated to inputs that could be appropriately and transparently utilized by the BatPaC model, as well as inform the modeling of learning effects.

Tesla also commented that "warranty cost reserves for our current generation of Model S & X are significantly lower than the figures assumed by the Agencies for BEVs through MY2025." Again, while encouraging, the comment does not provide adequate information to effectively assess or update the warranty cost figures used in the EPA analysis. Currently, the use of a relatively high indirect cost multiplier (ICM) for warranty reserves is based on the relative uncertainty associated with new technologies. While Tesla may be experiencing lower costs than this factor would suggest, it is unclear whether this experience will translate equally well to all manufacturers serving all segments and operating at widely varying production levels during the time frame of the rule.

Tesla Motors also provided comment regarding the projected size of battery packs, an important determinant of their cost. Tesla stated, "the battery capacity assumed in the TAR to achieve 200 miles of electric range is overstated, resulting in an inflated total cost figure for the battery pack. The Agencies estimate that it will take 56kWh of energy storage to achieve 200 miles of electric range in a Small MPV, however, our technology achieves more than 200 miles of range with a smaller battery capacity than the TAR's 2025 estimates."

EPA has reexamined the inputs and assumptions to the battery sizing methodology and believes that the updated analysis conducted for this Proposed Determination more accurately projects the needed capacity of battery packs for all modeled PEVs. The updates and their effect on battery sizing are discussed in Chapter 2.3.4.3.7 (Cost of Batteries for xEVs).

Regarding the acceleration performance of modeled PEVs, Mercedes-Benz commented, "The electric vehicle powertrains assumed in EPA's analysis are undersized compared to what would be required to match the performance of a conventional vehicle's powertrain. This undersized powertrain results in significantly lower cost than would be required, which in turn underestimates our fleet level cost. As a part of the MTE, the agencies should revisit … the assumptions regarding Mercedes-Benz vehicle performance and future reduction potentials. Mercedes-Benz recommends that the agencies develop unique performance criteria for each vehicle in a manufacturer's fleet consistent with the performance of the vehicles in the baseline fleet that are being replaced."

The context of this comment suggests that it refers specifically to the observation that Mercedes-Benz vehicles tend to have a greater acceleration performance than most of the conventional vehicles that form the baseline fleet from which average PEV acceleration targets were derived, and that because of this, the PEV battery and non-battery sizings that EPA applies to an average vehicle in each class would not as faithfully represent the higher performance vehicles typical of the Mercedes-Benz fleet.

EPA acknowledges that different manufacturers target different levels of performance in order to accommodate the requirements of customers in the market they choose to serve. This is also true for other vehicle attributes, such as styling, luxuriousness, cargo capacity, towing capability, and so on. The EPA analysis, particularly as modified for this Proposed Determination, attempts to account for variations in performance by defining six vehicle classes that are distinguished by differences in power-to-weight ratio and road load. While this improves the ability of the analysis to represent much of the variation in performance across the overall fleet, some particularly high-performance (and, potentially, low-performance) product lines may not be represented as well. While modeling the performance of every individual vehicle in each manufacturer's fleet might be an ideal approach, the need to conduct the analysis in a practical manner requires the aggregation of vehicles into a limited number of groups. Particularly with respect to the battery and motor sizing problem, the EPA battery analysis already designs battery packs and specifies power output for 150 modeled PEVs, which would multiply dramatically if the analysis were extended to include individual manufacturers' fleets.

EPA also acknowledges that some PEV models may be targeting higher 0-60 acceleration targets than seen in comparable conventional vehicles, and that some PEV manufacturers, particularly those in the premium segment, appear to be marketing improved acceleration as an advantage of electrified vehicles. It remains to be seen, however, whether this trend will be as pronounced in the consumer segment over the longer term. As described in Chapter 2.3.1.2 (Performance Assumptions), throughout the Draft TAR and previous analyses, EPA has taken the approach of modeling GHG-reducing technologies as being implemented in a performance-neutral manner. Whether or not manufacturers do increase 0-60 acceleration time for PEVs compared to conventional vehicles, all PEVs are likely to offer faster response "off the line" and at lower speeds, due to the high low-end torque of the electric motor, which means that some performance advantage is likely to be present even if 0-60 times are not substantially increased.

2.3.4.3.7.1 Battery Sizing Methodology for BEVs and PHEVs

This section describes how EPA specified battery packs for modeled BEVs and PHEVs (referred to collectively here as PEVs). For HEVs, EPA used a different methodology that is described in the next section.

Specifying a PEV battery pack primarily involves determining the necessary energy storage capacity (in kWh) and power capability (in kW) to provide a desired driving range and level of acceleration performance. Energy storage capacity has a strong influence on the weight of the pack as well as its overall cost because it determines the amount of active energy storage material that must be included in the battery. Power capability has an influence on weight and also has a strong influence on cost because it determines how the materials are arranged as well as the relative proportion of active materials to inactive materials in each cell.

Because most PEV battery chemistries are known to experience degradation in power and energy capacity over time (also known as power fade and capacity loss respectively), it is also important to consider how performance at end-of-life might differ from beginning-of-life, and consider the need for increasing the target capacity or power to ensure that performance goals can be met for the life of the vehicle.

The choice of battery energy capacity is primarily a function of the energy efficiency of the vehicle and the target driving range. Because range may decline over time due to battery degradation, this raises the question of whether the target range should be considered a beginning-of-life or end-of-life criterion. Current regulatory practice, as exemplified by the EPA labeling guidelines for PHEVs and BEVs,[605] measures range at beginning-of-life and omits any adjustment for future capacity degradation. For PHEVs, however, current regulatory practice for the EPA GHG standards effectively requires vehicle manufacturers to consider degradation in range as it will directly affect the calculated in-use emissions if tested for compliance at any time during full useful life.[TTT] Accordingly, for PHEVs, manufacturers may use a combination of

[TTT] As noted in Section 2.3.4.3.4, PHEV GHG emissions are calculated using the SAE J1711 utility factor and AER. Accordingly, if range degrades during useful life, the utility factor correction would change and thus, the calculated GHG emissions would increase. As EPA's GHG emission standards are full useful life standards and battery oversizing and an energy management strategy that provides for a consistent range throughout the useful life. For BEVs, however, rather than oversizing the battery sufficiently to maintain the original EPA range over time, manufacturers have tended to make the customer aware of the possibility of range loss and in some cases have warranted the battery to a specified degree of capacity retention over a specified period of time. For example, Nissan warrants their 24-kWh Leaf battery to retain nine of 12 capacity bars (corresponding to about 70 percent capacity) for 60 months or 60,000 miles, and warrants their 30-kWh battery for 96 months or 100,000 miles. As another example, Tesla does not warrant against a specific degree of capacity loss but makes it clear that some capacity loss is normal and provides the customer with recommendations for preserving battery capacity.

The choice of battery power capability is primarily governed by vehicle performance expectations. In the case of BEVs and many longer-range PHEVs, the battery is sufficiently large that its power capability is likely to naturally exceed that needed for acceleration performance alone. These batteries effectively have a power reserve that provides a natural buffer against power fade. Smaller batteries, such as those of shorter-range PHEVs, may lack this advantage and may need to be sized deliberately to meet a target power capability, in which case power fade should be factored in to the sizing process because it could lead to loss of performance and loss of utility factor over the life of the vehicle.

As discussed in the Draft TAR, at the time of the 2012 FRM, the task of assigning battery capacity and power for the many PEV configurations to be analyzed was a very difficult task, with few well-developed techniques and tools available. Further, it was necessary to choose assumptions to reflect an expected state of technology in the 2020 to 2025 time frame, even though few production vehicles were available at the time to either serve as a reference for the current state of technology or to establish trends for its advancement. The EPA methodology therefore employed a wide variety of simplifying assumptions and estimation methods in order to conduct the effort in a practical way while using calculation tools that are easily accessible to external reviewers.

The Draft TAR reviewed in detail the method originally used in the 2012 FRM and the improvements that were implemented for the Draft TAR analysis. Readers interested in the origin of the method and the changes applicable to the Draft TAR analysis may refer to the Draft TAR, Section 5.3.4.4.7.

After completion of the Draft TAR, public comments and updated information led to a number of updates to the methodology and assumptions as employed in this Proposed Determination analysis. The discussion below focuses on reviewing the core methodology, followed by a description of the updates.

The EPA battery and motor sizing analysis is a spreadsheet-based method that determines battery energy capacities and power capabilities for a large array of modeled PEVs. Because battery capacity and power requirements are strongly influenced by vehicle weight, and battery weight is a function of capacity and power while also being a large component of vehicle weight,

vehicles are considered noncompliant if their emissions exceed the certified emission level by more than 10 percent during the useful life, manufacturers must account for degradation or risk exceeding the GHG standards in-use.

sizing the battery for a BEV or PHEV requires an iterative solution. This problem is well suited to the iteration function available in common spreadsheet software. A spreadsheet-based methodology was therefore selected as being sufficiently powerful while remaining accessible to public inspection using standard commercially available software. EPA used Microsoft Excel for this purpose, with the Iteration setting enabled and set to 100 iterations.

The EPA approach begins by defining a large group of example PEVs for which battery packs are then specified in detail and analyzed for direct manufacturing cost. The array of PEVs includes five electrified vehicle types (BEV75, BEV100, BEV200, PHEV20, and PHEV40), six baseline vehicle classes represented by different curb weights, and five levels of target curb weight reduction (0, 2, 7.5, 10, and 20 percent). This results in a total of 150 PEV instances,[UUU] each characterized by a driving range, a baseline curb weight, and a level of target curb weight reduction, as shown in Figure 2.118. A sizing spreadsheet determined battery energy capacities and battery power requirements for each vehicle, in conjunction with ANL BatPaC which determined battery specific energy (kWh/kg) for use by the sizing spreadsheet, and ultimately a pack cost estimate. Pack cost, electric drive power ratings, and the necessary level of mass reduction applied to the glider (the baseline vehicle minus powertrain components) for each vehicle were then utilized by the OMEGA model.

[UUU] For each of the 150 vehicles, two battery cathode chemistries (NMC622 and blended LMO/NMC) and four production volumes (50K, 125K, 250K and 450K) were also considered, resulting in the generation of 1,200 individual battery cost estimates.

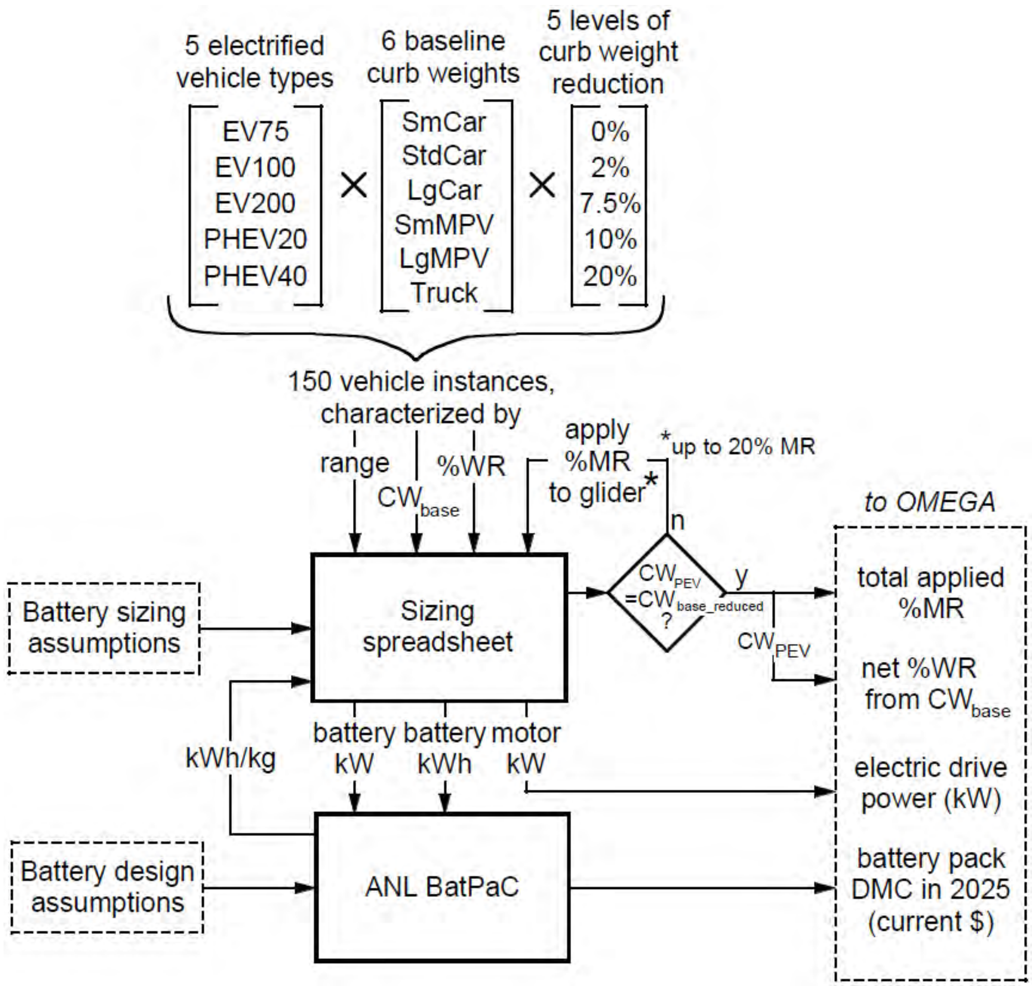


Figure 2.118 EPA PEV Battery and Motor Sizing Method

Method for Sizing of Battery Energy Capacity

Battery energy capacity was considered to be a function of desired driving range (mi) and vehicle energy consumption (Wh/mi).

Driving range was defined by the various range configurations (BEV75, BEV100, BEV200, PHEV20, and PHEV40) and was considered to be an approximate real-world, EPA-label range. As in the Draft TAR analysis, this Proposed Determination analysis considers PHEV40 range to be an all-electric range without assistance from the engine under any vehicle operating conditions, while the PHEV20 range is an effective electrically-powered range resulting from a blended-operation architecture.

Energy consumption was estimated by taking into account the weight of the battery necessary to deliver this range, and many other factors.

To estimate energy consumption for a given PEV instance, first its curb weight was estimated as equal to the curb weight CW_{base} of the corresponding baseline conventional vehicle, modified by any applicable curb weight reduction WR_{target} (0, 2, 7.5, 10, or 20 percent), and further modified by subtraction of the weight of conventional powertrain components (for BEVs) and addition of the weight of electric content (for BEVs and PHEVs), as shown in Equation 4 through Equation 7.

Equation 4. Target curb weight reduction

$$WR_{target} = \%WR * CW_{base}$$

Equation 5. Weight-reduced curb weight

$$CW_{base\_reduced} = CW_{base} - WR_{target}$$

Equation 6. Raw curb weight of BEV

$$CW_{BEV} = CW_{base\_reduced} - W_{ICE\_powertrain} + W_{electric\_content}$$

Equation 7. Raw curb weight of PHEV

$$CW_{PHEV} = CW_{base\_reduced} + W_{electric\_content}$$

The curb weights CW_{base} of conventional baseline vehicles were derived from the baseline fleet for a set of six vehicle classes corresponding to the vehicle classes used in the LPM.

The assumed weights of the removed conventional powertrain components (called "weight delete," or $W_{ICE\_powertrain}$) varied for each of the six vehicle classes, as an approximate function of power. Electric content weight ($W_{electric\_content}$) consisted of estimated battery weight and electric drive weight (motor and power electronics). Since the weight of this content is strongly influenced by total vehicle weight and many other variables, it is not a constant figure but is iteratively computed by the spreadsheet. The computation utilized estimates of battery specific energy and estimates of the specific power of traction motors and power electronics applicable to the 2020 to 2025 time frame. In practice, the specific energy of a battery pack will vary depending on its power-to-energy (P/E) ratio and its energy capacity. In general, smaller more power-optimized batteries tend to show a lower specific energy than larger energy-optimized batteries. The analysis utilizes a direct link to ANL BatPaC to pull in dynamically updated values for battery specific energy. For BEVs, a gearbox weight of 50 pounds was also added.

To estimate the weight of non-battery components, EPA referred to performance targets for non-battery components published by US DRIVE. US DRIVE[606] is a consortium involving the U.S. Department of Energy, USCAR (an organization of the major U.S. automakers), and several other organizations including major energy companies and public energy utilities. This industry collaboration has established a number of cost and performance targets for automotive traction motors, inverters, chargers, and other power electronics components for the 2015 and 2020 time frames.[607] These include targets for specific power of electric propulsion motors and power electronics, both separately and alone, as shown in Table 2.105. These metrics are particularly relevant to the problem of component sizing.

Table 2.105 U.S. Drive Targets for Non-Battery Specific Power for 2015 and 2020

Component	U.S Drive Target (kW/kg)	
	2015	2020
Electric motor and power electronics	1.2	**1.4**
Electric motor alone	1.3	1.6

Power electronics alone	12	14.1

Since the EPA battery sizing methodology does not distinguish the power rating of the power electronics from that of the drive motor, the US DRIVE target that would be most relevant to the battery analysis is the specific power of electric motor and power electronics combined, which US DRIVE places at 1.4 kW/kg for the 2020 time frame. The method therefore estimates the weight of non-battery PEV components at 1.4 kW/kg.

As described in the Draft TAR, this figure has some support in the literature. A presentation by Bosch[608] at The Battery Show 2015 states that the electric motor and power electronics for a 100 kW, 20 kWh BEV system in the 2025 time frame is expected to comprise about 37 percent of electric content weight, with battery weight comprising the remaining 63 percent. Assuming the 20 kWh battery pack has a specific energy of about 140 Wh/kg (as indicated by BatPaC for an NMC622 pack at 115 kW net battery power), and a corresponding weight of 143 kg, the non-battery content would be estimated at about 53 kg. The 100 kW system would then represent 100 kW/53 kg or 1.88 kW/kg, making the US DRIVE figure of 1.4 kW/kg appear conservative.

Although the US DRIVE figures are targets and therefore not necessarily indicative of industry status, EPA has confidence that the targets for specific power represent attainable goals during the 2022 to 2025 time frame. This is based in part on the observation that the 2020 specific power target for electric motor and power electronics combined is very close to levels that were already being attained by some production vehicles at the time they were set.[609] Also, confidential business information conveyed to EPA through private stakeholder meetings with OEMs conducted since the FRM suggests that some of these targets are already being met or exceeded in production components today, or are expected to be met within the time frame of the rule.

The "raw" curb weight calculations of Equation 6 and Equation 7, if used directly, would typically generate estimated PEV curb weights that are significantly larger than the curb weights of the baseline vehicles on which they are based, due to the added weight of the large battery which may weigh more than the removed components. For several reasons noted below, EPA chose to further constrain the iteration by forcing the projected curb weight (CW_{BEV} or CW_{PHEV}) of each PEV to match the curb weight ($CW_{base\_reduced}$) of the corresponding baseline vehicle. In order to achieve this objective, EPA solved for the exact percentage of mass reduction that would need to be applied to the glider in order to offset the difference in curb weight, and applied that level of mass reduction to cause the curb weights to match. In cases where more than 20 percent mass reduction technology would have been necessary to offset the difference, it was capped at 20 percent and only in these cases was the curb weight of the electrified vehicle allowed to vary.

In part, EPA chose to constrain the PEV curb weights because it helps to differentiate between “applied” mass reduction and “net” curb weight reduction throughout the analysis. EPA differentiates between applied and net reduction because they are used in different ways in the analysis. Net curb weight reduction refers to a reduction in curb weight, and is used for estimating energy consumption. Applied mass reduction refers to percentage mass reduction applied to the glider, and is used for estimating the cost of mass reduction technology that has been embodied in the vehicle. Often, to achieve a given amount of net curb weight reduction, more mass reduction technology might need to be applied to electrified vehicles than to conventional vehicles because of the added weight of the electric content.

For example, as shown in Table 2.106, a BEV200 that benefits from application of 20 percent mass reduction technology to the glider may achieve a net curb weight reduction of only about 13 percent. In such a case, EPA would base the estimate of BEV200 mass reduction technology costs on a 20 percent applied mass reduction, while basing the estimate of BEV200 battery and motor costs on battery and motor sizings that are based on the energy and power requirements associated with only a 13 percent net curb weight reduction.

Table 2.106 Example Net Curb Weight Reduction for BEVs and PHEVs With 20% Mass Reduction Technology Applied to Glider

	BEV75	BEV100	BEV200	PHEV20	PHEV40
Curb weight reduction achieved by application of 20% MR tech					
Wt Class 1	20%	19%	13%	10%	6%
Wt Class 2	20%	19%	13%	11%	6%
Wt Class 3	20%	19%	13%	11%	6%
Wt Class 4	20%	19%	13%	10%	5%
Wt Class 5	20%	18%	12%	11%	5%
Wt Class 6	20%	18%	14%	10%	5%

In theory, rather than constraining the PEV curb weights, a similar result could have been achieved by applying the various weight reduction cases directly to the glider and allowing the curb weights to grow as they might. This would have generated a different set of applied and net reduction data points, with more data points representing little or no applied mass reduction, higher curb weight, and higher energy consumption and larger batteries as a result. However, because the high cost of battery capacity tends to improve the cost effectiveness of mass reduction technology in PEV applications, EPA expects that manufacturers are likely to implement significant mass reduction in most PEVs, meaning that cases with little or no applied mass reduction are of limited interest to the analysis. The chosen method generates a greater density of points at the higher percentages of applied weight reduction that are most likely to represent industry practice.

After determining the PEV curb weight (which in most cases was constrained to match the baseline curb weight, but now carries a specific degree of applied mass reduction in order to do so), the method then computes the loaded vehicle weight (also known as inertia weight or equivalent test weight (ETW)) by adding 300 pounds to the curb weight:

Equation 8. Equivalent test weight (ETW) of PEVs

$$\mathrm{ETW_{PEV}}(lb) = \mathrm{CW_{PEV}}(lb) + 300$$

The method then uses this test weight to develop an energy consumption estimate. First, it estimates the fuel economy (mi/gal) for a conventional light-duty vehicle (LDV) of that test weight by a regression formula derived from the relationship between 2-cycle fuel economy and inertia weight. Compiled data on fuel economy vs. test weight from the EPA Trends Report provided the primary data source. From this data, EPA then derived a polynomial regression formula for fuel economy (mi/gal) as a function of ETW, the format of which is shown in

Equation 9. Specific coefficient values of A, B, and C used for the Draft TAR and revised for this Proposed Determination analysis are listed in a later discussion.

Equation 9. MY2008 conventional LDV fuel economy regression formula

$$FE_{conv}(mi/gal) = \mathrm{A} \times \mathrm{ETW_{PEV}}^2 - \mathrm{B} \times \mathrm{ETW_{PEV}} + C$$

This was then converted to a gross Wh/mile figure, assuming 33,700 Wh of energy per gallon of gasoline as shown in Equation 10:

Equation 10. Gross energy consumption (Wh/mile)

$$E_{gross\_FTP}(Wh/mi) = (\frac{1}{FE_{conv}}) \times 33{,}700$$

This figure was then brought into electrified vehicle space by applying a series of adjustments representing assumed differences in energy losses between conventional vehicles and electrified vehicles. This required making assumptions for several powertrain efficiencies:

(a) Brake efficiency: For conventional vehicles, this is the percentage of chemical fuel energy converted to energy at the engine crankshaft. For electrified vehicles, it is the percentage of stored battery energy converted to shaft energy entering the transmission. It therefore includes battery discharge efficiency and inverter and motor efficiency.

(b) Driveline efficiency: the percentage of brake energy entering the transmission and delivered through the driveline to the wheels. It includes transmission efficiency and downstream losses (such as wheel bearing, axle, and brake drag losses), but not tire rolling resistance.

(c) Cycle efficiency: the percentage of energy delivered to the wheels that is used to overcome road loads in moving the vehicle (that is, the portion of wheel energy that is not later lost to friction braking). This efficiency is larger for vehicles with regenerative braking.

The efficiencies assumed for baseline conventional vehicles were based on efficiency terms derived from EPA's lumped parameter model (LPM). Values for electrified powertrain efficiencies for BEVs and PHEVs of varying battery sizes were chosen in order to represent expected component efficiencies and to achieve a reasonable estimate of electrified energy consumption as indicated by the resulting battery capacity projections. Specific values can be inspected in the EPA Battery Analysis spreadsheets which are available in Docket EPA-HQ-OAR-2015-0827.

PEV road loads were also adjusted relative to conventional vehicles to represent assumed reductions in aerodynamic drag and rolling resistance applicable to these vehicles. PEVs were assigned a 20 percent reduction in both aerodynamic drag and rolling resistance from 2008 baseline levels. The effect was estimated by the LPM and then applied to the computed road load. Because the LPM estimates that a 20 percent improvement in aerodynamic drag and rolling resistance will reduce road loads to approximately 90.5 percent of baseline, road loads were reduced by that amount. The effect of reductions in curb weight were not estimated by the LPM but instead were inherently represented by use of the ETW regression formula to convert curb weights into base energy consumption estimates.

The combined effect of these steps means that the estimated energy consumption of each PEV is therefore derived from the energy consumption of a corresponding baseline conventional vehicle by applying a ratio of the road loads of the PEV ($\%Roadload_{PEV}$) to those of the baseline vehicle ($\%Roadload_{conv} = 1$) and a ratio of the assumed efficiencies (η) of the respective powertrains, as shown in Equation 11.

Equation 11. PEV unadjusted energy consumption

$$E_{P/EV\_FTP}(Wh/mi) = E_{gross\_FTP} * \left(\frac{\%Roadload_{P/EV}}{\%Roadload_{conv}} * \frac{\eta_{vehicle\_conv}}{\eta_{vehicle\_P/EV}}\right)$$

Equation 11 yields a laboratory (unadjusted) two-cycle FTP energy consumption estimate. To represent a real-world energy consumption, the analysis applies a derating factor to convert unadjusted fuel economy to real-world fuel economy. The EPA range labeling rule specifies a default derating factor of 70 percent, with provisions for using a different (custom) factor based on optional 5-cycle testing. This analysis applied a varying derate value depending on vehicle configuration, as described later.

Applying the derate factor (as shown with an example value of 70 percent in Equation 12) results in the PEV on-road energy consumption estimate that the method uses to determine the required battery pack capacity for the vehicle.[VVV]

Equation 12. PEV on-road energy consumption

$$E_{onroad}(Wh/mi) = E_{P/EV\_FTP} * (\frac{1}{0.70})$$

Finally, as shown by Equation **13**, the method determines the required battery energy capacity (BEC) as the on-road energy consumption in Wh/mile, multiplied by the desired range in miles, divided by the usable portion of the battery capacity, or usable SOC design window. The assumed usable SOC design window (*SOC%*) varied between BEVs and PHEVs and is discussed in a later section.

$$BEC(Wh) = \frac{E_{onroad}(\frac{Wh}{mi}) \times range(mi)}{SOC\%}$$

Equation 13. Required battery pack energy capacity for PEVs

As mentioned previously, the intensively iterative nature of the battery capacity sizing problem means that all of the preceding calculations are constructed in a spreadsheet as circular references and performed iteratively by the spreadsheet software until the estimated weights, ranges, and energy consumption figures converge.

Method for Sizing of Battery Power Capability

[VVV] As described later, this Proposed Determination analysis uses a 70 percent factor for most PEVs but applies a custom derating factor of 75 percent for BEV200 based on examples of recent industry practice.

Another input to the battery sizing process is the required power capability of the battery. Battery power capability was derived from an assigned peak motor power, which in turn was considered to be a function of desired acceleration performance.

PHEV40 was conceptualized as a range-extended electric vehicle, with a motor and battery sized to be capable of providing pure all-electric range in all driving situations. PHEV20 was modeled as a blended-operation vehicle where the motor is often assisted by the engine during the charge depletion phase. This means that PHEV40 motor power ratings in this analysis are likely to be higher than would apply to a blended-operation PHEV40. PHEVs were configured with a single propulsion motor, in contrast to some production PHEV designs that split the total power rating between two motors. Most PHEVs also include a second electric machine used primarily as a generator. The analysis does not explicitly assign a weight to this component but considers it as part of the weight of the conventional portion of the powertrain, which retains its original weight despite the likelihood of downsizing in a PHEV application.

Acceleration performance was represented by assigning a power-to-weight ratio calculated for each vehicle class. This meant that once the curb weight for a PEV was estimated, a simple linear calculation determined the peak motor power needed to meet the target power-to-weight ratio. The battery power was then estimated as 15 percent greater than the peak motor power, to account for losses in the motor. As with battery capacity, motor and battery power both interact with battery and vehicle weight, and the calculation must be performed iteratively in the spreadsheet as part of the overall battery sizing process.

Updates to Battery Sizing Assumptions and Methodology for the Proposed Determination Analysis

As discussed in the Draft TAR, in the time since the 2012 FRM, the emergence of a variety of production PEVs provided an opportunity to validate the assumptions and methods of the 2012 FRM analysis. The Draft TAR analysis therefore incorporated a large number of changes to the methods and input assumptions for assigning battery capacity, battery power, motor power, and other aspects of the PEV modeling problem. The major changes in going from the 2012 FRM to the Draft TAR analysis included improvements to weight estimation for battery and non-battery components, improvements to the assignment of electric drive motor power, increases in usable battery capacity and electric drive efficiency, refinements to battery power ratings, variation of range derating factors, and changes to certain PHEV powertrain configurations. These changes were described in detail in the Draft TAR. Readers interested in the details of these changes may refer to the Draft TAR. Because many of the resulting changes were retained for this Proposed Determination analysis, the Draft TAR may also be useful in understanding the rationale behind many of the decisions regarding inputs and assumptions applicable to this Proposed Determination battery analysis.

The following sections detail the updates in methods and assumptions that EPA made for this Proposed Determination analysis.

The public comment period on the Draft TAR elicited a number of comments regarding the Draft TAR battery analysis methodology and assumptions. Where applicable, EPA has refined and updated the methodology and assumptions as suggested by these comments and by updated information that became available since the Draft TAR analysis was developed.

In general, one message of the various public comments relating to the battery analysis suggested that the projected battery sizing and battery costs per kWh were too high (i.e. too conservative) compared to a growing industry consensus. For example, as previously described, Tesla Motors suggested that projected battery sizing for a BEV200 was larger than necessary. Other commenters suggested that some of the cost per kWh projections in the Draft TAR appeared to be higher than more recent estimates from other sources. The bulk of comments relating to battery costs were qualitative in nature and did not provide specific new information that had not been available to EPA in developing the estimates. However, when taken in conjunction with trends EPA has continued to observe in third-party projections of future battery costs (from continued monitoring of the industry since the publication of the Draft TAR), EPA believed that it would be valuable to reexamine the battery sizing and costing estimates.

Based on regular attendance at technical conferences during 2016 and particularly after completion of the Draft TAR, EPA has become increasingly aware of examples of formal and informal industry battery cost projections that parallel or even undercut the projected cost per kWh for BEV batteries projected in the Draft TAR for the 2020 time frame and beyond. For example, Ford has been reported as estimating its future battery system costs at $120 per kWh by 2020 and as low as $85 per kWh by 2030;[610] an expectation of about $100 per kWh at the cell level by 2020 was related verbally during a talk by a Ford representative at the 2016 Battery Show;[611] while at the same show, Berenberg Bank predicted $170 per kWh at the pack level by 2020[612] and a presentation by Bloomberg New Energy Finance included scenarios by which $155 per kWh might be approached by 2020.[WWW] These examples as well as the frequency with which such examples are being encountered reinforced the conclusion that battery costs are continuing to change rapidly, and that EPA should therefore update its battery cost projections for the Proposed Determination analysis.

Updated information on the 2017 Chevy Bolt suggested another update to the analysis. After EPA certification of the Chevy Bolt in late 2016, EPA considered the derating factor that was used in the certification process to compute the label range from the laboratory test results. Certification data suggested that this vehicle utilized the default 70 percent derating factor, rather than a higher custom factor as the Draft TAR analysis had assumed would apply to BEV200. EPA used this updated information to update the derating factor assumed for BEV200 in this analysis to a lower figure.

EPA also added to its compilation of MY2012-2016 BEVs and PHEVs several new models that were released or certified after completion of the Draft TAR. This had small effects on some comparative charts and the motor power estimation formula that was used to specify traction motor peak power ratings for PEVs.

EPA also considered updated information regarding maximum battery cell capacities being used in some production vehicles, and updated information regarding certification practices for PHEVs that may affect design of the battery capacity for a given range.

As part of the effort to address other comments received on the EPA GHG analysis in general, EPA also refined the six LPM class definitions. This resulted in changes to the target curb

[WWW] Bloomberg declined to include this presentation in the conference proceedings.

weights and power-to-weight ratios for each modeled xEV as compared to those used in the Draft TAR, which in turn has some effect on projected costs.

Specific Updates to Inputs and Assumptions for this Proposed Determination Battery Analysis

Several updates were motivated in part by public comments suggesting that projected battery costs were too conservative in light of recent industry estimates. In the Draft TAR, EPA compared the projected cost per kWh for BEV200 battery packs to other sources such as the Nykvist & Nilsson study and the GM/LG cost announcement. In so doing, EPA recognized that the Draft TAR cost projections may be somewhat conservative, as would befit projections made in the face of future uncertainty. EPA also recognized that projections of battery capacity for a given vehicle weight and range target were in many cases somewhat larger (i.e. conservative) than seen in some production vehicles. At the time, it was felt that a somewhat conservative estimate for both would be appropriate given the uncertainties associated with future cost estimation.

Several commenters argued that battery costs have fallen at a faster rate than anticipated, and would continue to fall to perhaps below the levels projected in the Draft TAR. Tesla Motors also referred to current and future vehicles that are anticipated to have lower cost per kWh and/or smaller packs for a given range target. Although the comments did not provide detailed data such as evidence of actual pack costs for specific vehicles or types of vehicles, these comments suggested that the conservative nature of the existing projections should be re-examined, as the effect might be magnified by the projection of larger pack capacities than necessary.

EPA is committed to maintaining the accuracy of battery cost projections as much as available information allows. This Proposed Determination analysis therefore makes several updates to the battery sizing and costing analysis with the primary goal of refining and updating projected battery sizing and cost. These included the following primary updates:

(a) Improved Basis for PEV Energy Consumption Estimates

In September 2016, EPA delivered a presentation at The Battery Show 2016[613] describing the battery analysis presented in the Draft TAR. The presentation acknowledged that, by some measures, the battery sizes projected in this analysis were larger than those seen in some production vehicles of a similar weight and driving range (i.e. conservative). The presentation concluded that the gap might be narrowed by improving the method by which energy consumption of the modeled PEVs was predicted. However, due to the need for compatibility with other analyses that the battery cost model feeds into, only limited options were available for improving the energy consumption estimates.

As a first step in this direction, EPA chose to use the most recent version of the EPA Trends Report to derive the polynomial regression for fuel economy-to-ETW that formed the basis for PEV energy consumption estimates. Adopting an updated Trends dataset serves to empirically account for improved efficiencies and road load characteristics present in today's baseline fleet and bring them into the battery sizing analysis. This was expected to reduce the estimated base energy consumption compared to the old method. (As described later, application of road load technologies to this base energy consumption was also adjusted to reflect technology already present in the fleet. Even after this adjustment, the updated polynomial regression resulted in improved estimates compared to the Draft TAR).

Equation 14 shows the updated coefficients that were used in the polynomial regression equation in this Proposed Determination analysis.

Equation 14. MY2015 conventional LDV fuel economy regression formula used in Proposed Determination

$$FE_{conv}(mi/gal) = 0.0000005308 \times \mathrm{ETW_{PEV}}^2 - 0.0122335420 \times \mathrm{ETW_{PEV}} + 73.4948$$

As another step, EPA updated the version of the LPM that was used in the battery analysis spreadsheets for estimating the road load reduction resulting from the 15 percent application of aerodynamic and rolling resistance technology. The 2016 version of the LPM includes significant refinement and calibration compared to the older version used in the Draft TAR battery analysis, and was expected to result in more accurate energy consumption estimates.

EPA also modified the method for estimating the road load effect of net curb weight reduction. Previously, changes in curb weight were converted to a road load reduction via the LPM. In the revised analysis, the LPM no longer serves in this role, but instead, the reduced curb weights generated by a given application of mass reduction are converted to an energy consumption effect by simply feeding them directly to the FE-to-ETW polynomial regression formula. This represents a more empirical approach to converting weight deltas to fuel economy improvements.

EPA also made an effort to further optimize the various powertrain efficiency conversion factors by which fuel economy estimates (generated by the polynomial regression formula, in mi/gal) were converted to an electrified energy consumption estimate (in Wh/mi). This process was guided by engineering judgement regarding expected electrified component efficiencies present or anticipated for the 2022 to 2025 time frame, and validated by careful analysis of the resulting projected battery capacities for a given range target and curb weight. Ultimately, the selected efficiencies were seen to result in battery capacity projections that closely parallel the capacities seen in recent production xEVs of the same weight and range. For more information on the specific values used, please see the EPA Battery Analysis (Proposed Determination) spreadsheets which are available in Docket EPA-HQ-OAR-2015-0827.

(b) Accounting for Road Load Reduction Technology Already Present in the Fleet

Several commenters to the Draft TAR (in the context of the greater GHG analysis rather than the battery analysis) pointed out that a certain amount of mass reduction, aerodynamic drag reduction and rolling resistance reduction are likely present in the baseline fleet and should be accounted for in establishing the remaining amount that may be applied. This would affect the battery analysis in that varying amounts of mass reduction are applied to xEVs, up to a cap of 20 percent total mass reduction. The analysis also applies a 20 percent reduction in aerodynamic drag and rolling resistance. If some amount of these technologies are already present in the fleet from which target curb weights and energy consumption estimates are derived, then the maximum allowable application should be modified in order not to exceed the intended levels.

EPA modified the curb weight inputs to the battery analysis to assume that approximately 2 percent mass reduction is already present in the MY2015 baseline fleet from which input curb weight targets are derived. This was based on an informal analysis of assumed weight reductions for individual vehicles in the MY2015 baseline, which averaged approximately 2 percent. The 2 percent mass reduction assumed to be present was then added back to the glider weight. This corrected weight was taken to be null, and used as the target curb weight. The analysis was then allowed to apply up to 20 percent total mass reduction, which would now include the 2 percent present in the fleet.

A similar adjustment was performed to account for aerodynamic drag and rolling resistance technologies. In the construction of technology packages for the OMEGA analysis, BEV and PHEV technology packages include an aerodynamic drag reduction of 20 percent (the technology case known as AERO2), and a tire rolling resistance reduction of 20 percent (the case known as LRRT2). This is based in part on the expectation that manufacturers will find these technology improvements to be highly cost effective for plug-in vehicles due to the potential to reduce the size and cost of the battery. The package costs thus are meant to include the cost of application of AERO2 and LRRT2 relative the 2008 baseline.

In the Draft TAR, the EPA battery analysis did not account for aerodynamic or rolling resistance technology already in the fleet, because the polynomial fuel economy regression was based on MY2008 Trends data, which by definition represents the null technology case. In updating the Trends energy consumption baseline to the 2015 Trend Report for this Proposed Determination analysis (as described under item (a)), it became more important to account for technology already in the Trends sample fleet. For this Proposed Determination analysis, EPA assumed that a 5 percent improvement in aerodynamic drag and rolling resistance was already present in the 2015 Trends Report baseline fleet. An additional 15 percent improvement was applied via the LPM.

(c) Updated Baseline Curb Weights and Vehicle Classes

Another factor that influenced battery costs and sizing was the EPA decision to redefine the definitions of the LPM classes. In the Draft TAR, xEVs were modeled for each of six LPM classes, which were defined roughly by vehicle size, including Small Car, Standard Car, Large Car, Small MPV, Large MPV, and Truck. For this Proposed Determination analysis, EPA redefined the LPM classes. More information on this update is described in Section 2.3.1.4.

Accordingly, target curb weights in this TSD battery analysis are now derived from the MY2015 baseline fleet (with PEVs removed) and aggregated into six distinct weight classes numbered 1 through 6. This means that the modeled xEVs of this Proposed Determination have significant differences in curb weight targets as compared to the now-defunct classes of the Draft TAR. As a result, figures computed for the Draft TAR are not directly comparable to those of this Proposed Determination analysis. To improve comparability, differences in projected cost between the Draft TAR and Proposed Determination analyses are now reported as an average across all of the LPM classes. The vehicle classes and curb weights previously used in the Draft TAR analysis are contrasted with those used in this Proposed Determination analysis in Table 2.107.

Table 2.107 Changes to Baseline Curb Weights from Draft TAR to Proposed Determination

Draft TAR		Proposed Determination	
Vehicle Class	Curb weight (lb)	Vehicle Class	Curb weight (lb)
Small Car	2628	Wt Class 1	2868
Standard car	3296	Wt Class 2	3340

Large car	4117	Wt Class 3	3613
Small MPV	3500	Wt Class 4	4062
Large MPV	4448	Wt Class 5	4902
Truck	5161	Wt Class 6	4911

(d) Changes to Power-to-Weight Ratios Resulting from LPM Classes

As a result of the changes to class definitions, the power-to-weight ratios for each of the xEV classes also changed. Although all xEVs continue to be modeled with acceleration capability comparable to the baseline average for each new LPM class, the elimination of the Large Car class (which previously had a relatively high power) means that the performance targets of the new classes define a somewhat narrower spectrum than before.

(e) Changes to ICE Weight Deletes Resulting from LPM Classes

The updated LPM class definitions also required modifications to the ICE powertrain weights ("weight delete," or $W_{ICE\_powertrain}$) assumed to be deleted from baseline vehicles in order to become a BEV. Weight deletes used in this Proposed Determination analysis were scaled from those used in the Draft TAR by performing a regression of the Draft TAR values with respect to the vehicle power levels they had been associated with, and mapped to the new power levels of the new LPM classes. Although the specific weight deletes for each class have therefore changed, the average weight delete as a percentage of curb weight across all classes was virtually unchanged from that of the Draft TAR. The new values for weight deletes are shown in Table 2.108.

Table 2.108 Baseline ICE-Powertrain Weight Assumptions (Pounds), By Vehicle Class

Class	Engine	Transmission*	Fuel system*	Engine mounts*	Exhaust	12V battery†	**Total**
Wt Class 1	273	141	56	25	22	28	**545**
Wt Class 2	316	153	62	25	25	31	**613**
Wt Class 3	335	159	66	25	26	33	**643**
Wt Class 4	388	174	74	25	30	37	**729**
Wt Class 5	439	189	82	25	33	41	**810**
Wt Class 6	456	193	85	25	35	43	**837**

Note:
*Transmission minus differential; fuel system 50% fill; engine mounts include NVH treatments.
†Although current BEVs retain a relatively small lead-acid 12V battery, this analysis, as did the Draft TAR analysis, deletes the ICE-sized battery and assumes that an improved solution by 2025 will have a relatively negligible weight compared to the other deleted components. Chapter 2.2.4.3.2 (Power Electronics) includes a discussion of drivers and trends toward improving the low-voltage battery in BEVs.

(f) Update to Maximum Cell Capacities

EPA also updated the maximum cell capacities for PEV battery packs. Based on the recent announcement and continued use of a 94 Ampere-hour cell in the BMW i3 BEV and Rex (PHEV), EPA became more confident of the potential for such large capacity cells to be used in future BEVs and longer-range PHEVs. EPA therefore increased the cell capacity limit for modeled BEV packs to about 90 A-hr level (formerly 75 A-hr in the Draft TAR), and increased the limit for PHEVs to about 60 A-hr (formerly 50 A-hr). Further, the limit was imposed as a maximum, rather than a preferred target, meaning that cell sizes now approach the maximum limit from below, rather than being scattered above and below the target. On average this results in somewhat larger cell capacities and fewer cells per pack, which in some cases results in somewhat lower pack costs for a given pack capacity.

(g) Update to Derate Factor for BEV200

For certification purposes, to convert a two-cycle range test result to a label value, EPA allows manufacturers to either use a default derating factor of 70 percent or to derive a custom derating factor by undergoing complete five-cycle testing. EPA certification data for 2012-2016MY BEVs indicates that most BEV manufacturers have chosen to apply the default 70 percent derating factor in their certification tests. Tesla Motors is the only BEV manufacturer that has elected to derive a custom derating factor. Tesla has used a factor of 79.6 percent for the standard Model S configurations from 60 kWh to 90 kWh, and a factor ranging from 73 to 76 percent for higher-performance and AWD configurations of the Model S and Model X.[XXX]

The Draft TAR battery analysis therefore had adopted a derate factor of 80 percent for BEV200, on the basis that Tesla was using a factor of 79.6 percent for the base Model S. Because manufacturers of BEV75 and BEV100-type vehicles have only used the default 70 percent derating factor and have not derived custom factors, EPA had retained the 70 percent derating factor for BEV75 and BEV100.

In the Draft TAR it was acknowledged that the appropriateness of an 80 percent derate factor in modeling the label range of future BEV200s would depend on the degree to which manufacturers are able to derive a custom derating factor similar to that used for certification of the base Tesla Model S. Since publication of the Draft TAR, the 2017 Chevy Bolt BEV completed EPA certification. Certification data indicates that this vehicle utilized a 70 percent (apparently default) derate factor in computing its certified 238-mile label range. Also, further certifications of Tesla vehicles including some variations of the Model S have continued to use lower derating factors of about 73 to 76 percent rather than the 79.6 percent of the base Model S.

These developments led us to reconsider the Draft TAR expectation that future BEV200s would commonly certify with an 80 percent derate factor. For this analysis, we therefore have reduced the assumed derate factor for BEV200 from 80 percent to 75 percent, similar to the factors used in recent Tesla certifications. EPA continues to believe that, as manufacturing volumes and the number of BEV models both increase, there remains a potential for manufacturers to justify the derivation of custom derate factors during the certification process, and that in many cases this may result in a derate factor greater than the default 70 percent.

(h) Update of Motor Power Sizing Equation By Addition of MY2017 Vehicles

Several xEV models that have entered the market since the completion of the Draft TAR have been added to the empirical study by which electric motor power and acceleration characteristics are assigned. These included the 2017 Chevy Bolt and the BMW i3 94 Ah. This resulted in a small change to the empirical equation for motor sizing. The change is small because the curb weight and acceleration levels of these vehicles fell very close to the curve developed for the

[XXX] As indicated by the ratio of adjusted (Guide) combined fuel economy to unadjusted combined fuel economy reported in columns M and P of the 'EVs' tab of the 2016 Fuel Economy Guide datafile, available in the Docket and at https://www.fueleconomy.gov/feg/download.shtml

Draft TAR equation. The updated equation used in this Proposed Determination is shown in Equation 15 below. Development of this equation is described in more detail in Section 2.2.4.3.6 (Relating Power to Acceleration Performance).

Equation 15. Empirical equation for 0-60 all-electric acceleration time of MY2012-2017 PEVs

$$t = 1.1321\left(\frac{kW}{kg\ ETW}\right)^{-0.733}$$

(i) Adjustment to Usable Battery Capacity of PHEVs to Account for Range Degradation

As the Draft TAR noted, the possibility of PHEV range degradation over the life of the vehicle is important to regulators and PHEV manufacturers, because range degradation would gradually change the utility factor, which is a factor in certification and GHG compliance. The Draft TAR analysis did not include an explicit oversizing factor for PHEVs. This Proposed Determination analysis adds a 15 percent oversizing factor to the usable capacity of PHEV batteries, by defining two usable SOC design windows, a smaller window applicable to beginning of life (BOL) and a larger window applicable at end of life (EOL). This is meant to capture practices to manage range degradation, which might include certifying with an aged battery, modification of usable SOC over the life of the vehicle, or limiting the usable SOC at time of certification. PHEV20 vehicles were assigned a BOL usable SOC window of approximately 65 percent and an EOL window of 75 percent. PHEV40 was assigned a BOL window of 67 percent and an EOL window of 77 percent. These figures were chosen by engineering judgement and by considering their effect on the ability of the sizing method to predict battery capacities of production PHEVs of a given range and curb weight.

Summary of Changes to Battery Sizing Assumptions

Table 2.109 reviews the major input assumptions to the EPA battery sizing method, and the changes that were made for this Proposed Determination analysis.

Table 2.109 PEV Battery Sizing Assumptions and Changes from Draft TAR to Proposed Determination

Assumption	Draft TAR	**Proposed Determination**
WC1 curb weight (Small Car in TAR)	2628 lb	**2868 lb**
WC2 curb weight (Std car in TAR)	3296 lb	**3340 lb**
WC3 curb weight (Lg car in TAR)	4117 lb	**3613 lb**
WC4 curb weight (SmMPV in TAR)	3500 lb	**4062 lb**
WC5 curb weight (LgMPV in TAR)	4448 lb	**4902 lb**
WC6 curb weight (Truck in TAR)	5161 lb	**4911 lb**
Applied aero reduction from 2008 baseline	20%	unchanged
Applied tire reduction from 2008 baseline	20%	unchanged
Applied mass reduction to glider from 2008 baseline	Varies; max 20%	unchanged
Short range BEV (mi)	BEV75	unchanged
Mid-range BEV (mi)	BEV100	unchanged

Long range BEV (mi)	BEV200	unchanged
Short range PHEV (mi)	PHEV20	unchanged
Long range PHEV (mi)	PHEV40	unchanged
Usable battery capacity, HEV	40%	unchanged
Usable battery capacity, PHEV20	70%	**65.2%**
Usable battery capacity, PHEV40	75%	**67%**
Usable battery capacity, BEV75	85%	unchanged
Usable battery capacity, BEV100	85%	unchanged
Usable battery capacity, BEV150/200	90%	unchanged
Battery specific energy	computed by BatPaC	unchanged
Non-battery specific power	1.4 kW/kg	unchanged
Motor sizing	Based on MY2014 baseline 0-60 performance estimate and new empirical equation for PEVs	**Updated to include MY2017 examples**
Brake efficiency, PEV	87%	**varies**
Driveline efficiency, BEV	95%	**varies**
Cycle efficiency, PEV	97%	**varies**
BEV battery power as fn of motor power	1.1x	unchanged
PHEV battery power as fn of motor power	1.1x	unchanged
Allowance for power fade	20%	unchanged
Road loads, PEV	from LPM	**from LPM and Trends**
2-cycle to 5-cycle derating factor, PHEV and BEV75/100	70%	unchanged
2-cycle to 5-cycle derating factor, BEV200	80%	**75%**
PHEV20 motor sizing basis	blended	unchanged

Analysis of Changes

The changes described above resulted in changes to the projected sizing of PEV batteries and motors compared to those of the Draft TAR. Table 2.110 shows examples of the battery capacities and motor power ratings generated by the revised sizing methodology and compares them to the corresponding estimates generated by the Draft TAR analysis.

Table 2.110 Example Changes in Projected PEV Battery Capacity and Motor Power, Draft TAR to Proposed Determination (20% weight reduction case)

	BEV75		BEV100		BEV200		PHEV20		PHEV40	
Draft TAR										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)
Small Car	17.3	54.0	23.5	55.6	41.2	60.6	6.1	29.7	11.7	61.9
Standard Car	21.4	83.8	29.1	86.2	50.2	93.4	7.5	45.8	14.4	96.3

Large Car	27.7	176.8	37.4	181.6	65.0	197.4	9.5	94.6	18.8	206.7
Small MPV	22.7	74.5	30.9	76.6	53.7	83.4	7.9	40.6	15.1	84.6
Large MPV	29.3	115.3	39.8	119.0	69.2	129.5	10.2	63.2	19.7	133.5
Truck	33.0	138.3	44.6	142.3	77.6	154.7	11.7	78.0	22.6	165.0
Proposed Determination										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)
Wt Class 1	16.4	66.0	22.0	65.9	37.9	65.5	6.2	32.7	12.4	65.1
Wt Class 2	17.8	87.4	23.9	87.3	41.4	86.7	6.8	43.3	13.7	86.1
Wt Class 3	18.7	96.7	25.1	96.6	43.6	96.0	7.2	47.9	14.5	95.3
Wt Class 4	20.3	124.2	27.3	124.0	47.6	123.3	7.9	61.4	16.2	122.3
Wt Class 5	23.9	149.0	32.4	148.7	56.8	151.2	9.5	73.8	19.8	146.7
Wt Class 6	23.9	158.0	32.5	157.7	58.6	156.8	9.5	78.2	20.0	155.6
Average change from Draft TAR										
	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)	Battery (kWh)	Motor (kW)
All classes	-24.8%	6.0%	-20.5%	2.9%	-19.9%	-5.5%	-11.0%	-4.1%	-5.6%	-10.3%

Notes:

†Compares BEV200 (Draft TAR) to BEV150 (FRM)

††Compares blended PHEV20 (Draft TAR) to EREV PHEV20 (FRM)

As shown by the selected examples in the following Tables, the pack-level specific energy figures EPA uses in this TSD analysis vary significantly, ranging from about 150 to 188 Wh/kg for BEV75 to BEV200 (assuming NMC622 cathode), to about 130 to 150 Wh/kg for PHEV40 (also NMC622), and about 115 to 125 Wh/kg for PHEV20 (assuming blended NMC/LMO cathode).

Table 2.111 Examples of Pack-Level Specific Energy Calculated By BatPaC for Selected PEV Configurations (0% WR)

	BEV75 (NMC622-G)		BEV100 (NMC622-G)		BEV200 (NMC622-G)		PHEV20 (NMC75%/ LMO25%-G)		PHEV40 (NMC622-G)	
	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio
Wt Class 1	152.5	4.6	165.3	3.4	174.3	2.1	119.7	6.5	152.7	6.6
Wt Class 2	157.2	5.5	160.0	4.1	178.3	2.5	118.0	7.7	148.3	7.9
Wt Class 3	160.1	5.7	171.1	4.3	181.0	2.6	119.4	8.0	147.9	8.2
Wt Class 4	163.7	6.5	160.3	4.9	184.9	3.0	119.1	9.2	129.9	9.6
Wt Class 5	168.3	6.3	172.7	4.7	187.3	2.8	124.6	8.8	138.0	9.1
Wt Class 6	166.1	6.6	172.6	5.0	187.3	3.0	123.4	9.3	135.2	9.6

Table 2.112 Examples of Pack-Level Specific Energy Calculated By BatPaC for Selected PEV Configurations (20% WR)

	BEV75 (NMC622-G)	BEV100 (NMC622-G)	BEV200 (NMC622-G)	PHEV20 (NMC75%/ LMO25%-G)	PHEV40 (NMC622-G)

	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio	Wh/kg	P/E ratio
Wt Class 1	151.6	5.3	160.3	3.9	171.2	2.3	118.0	7.0	150.1	6.9
Wt Class 2	150.3	6.5	163.7	4.8	174.3	2.8	119.6	8.4	145.3	8.3
Wt Class 3	152.4	6.8	165.7	5.1	176.3	2.9	116.0	8.8	144.3	8.7
Wt Class 4	150.0	8.1	169.0	6.0	179.7	3.4	114.5	10.3	135.4	10.0
Wt Class 5	153.1	8.2	170.9	6.1	167.6	3.5	118.2	10.3	133.1	9.8
Wt Class 6	150.3	8.7	168.7	6.4	188.0	3.5	117.0	10.8	130.6	10.3

While these figures may appear very aggressive compared to batteries seen in 2012-2017MY applications, it should be noted that the technology assumptions in BatPaC are forecasts for the 2020 time frame and EPA applies them to the year 2025. For comparison, in January 2016, GM announced that the 60 kWh Chevy Bolt BEV pack weighs 435 kg, suggesting that this BEV200 pack has already achieved a specific energy of 138 Wh/kg today.[614] The same specific energy was already seen in the 85 kWh Tesla Model S as early as 2012.[615] Similarly, the 18.4 kWh pack of the 2016 Chevy Volt PHEV weighs 183 kg, suggesting this PHEV53 pack has achieved 101 Wh/kg today. As has occurred in the time since the FRM, the level of industry activity in battery development suggests that similar advances are likely to continue through the 2022 to 2025 time frame.

To compare the Draft TAR capacity projections to specific production vehicles, Table 2.113 and Table 2.114 show the projected battery capacities and assumed curb weights for each electrified vehicle type and vehicle class at 0 percent and 20 percent nominal weight reduction, respectively. These tables are useful for drawing comparisons of the projected battery capacities to those of specific production BEVs and PHEVs. In the battery sizing analysis, differences in energy consumption among the six vehicle classes is primarily derived from differences in vehicle weight. Therefore matching a production vehicle's curb weight, range and battery capacity to the values in these tables provides a fair comparison regardless of whether the indicated classification or weight reduction case matches that of the vehicle.

Table 2.113. TSD Projected Battery Capacities and Assumed Curb Weights, 0% Nominal Weight Reduction

	BEV75 (NMC622)		BEV100 (NMC622)		BEV200 (NMC622)		PHEV20 (25NMC/75LMO)		PHEV40 (NMC622)	
	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh
Wt Class 1	2868	18.6	2868	24.8	2868	41.0	2868	6.6	2868	12.9
Wt Class 2	3340	20.7	3340	27.6	3340	45.7	3340	7.4	3340	14.3
Wt Class 3	3613	22.1	3613	29.4	3613	48.7	3613	7.8	3613	15.3
Wt Class 4	4062	24.6	4062	32.9	4062	54.4	4062	8.8	4048	16.9
Wt Class 5	4902	30.8	4902	41.0	4902	67.9	4902	10.9	4902	21.3
Wt Class 6	4911	30.8	4911	41.1	4911	68.1	4911	11.0	4911	21.3

Table 2.114 TSD Projected Battery Capacities and Assumed Curb Weights, 20% Nominal Weight Reduction

	BEV75 (NMC622)		BEV100 (NMC622)		BEV200 (NMC622)		PHEV20 (25NMC/75LMO)		PHEV40 (NMC622)	
	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh	Curb wt (lb)	kWh

Wt Class 1	2295	16.4	2322	22.0	2506	37.9	2571	6.2	2688	12.4
Wt Class 2	2672	17.8	2703	23.9	2903	41.4	2987	6.8	3137	13.7
Wt Class 3	2891	18.7	2928	25.1	3138	43.6	3231	7.2	3391	14.5
Wt Class 4	3249	20.3	3292	27.3	3519	47.6	3644	7.9	3851	16.2
Wt Class 5	3934	23.9	4008	32.4	4325	56.8	4377	9.5	4643	19.8
Wt Class 6	3945	23.9	4018	32.5	4229	58.6	4399	9.5	4680	20.0

The reasonableness of the battery capacity projections may be assessed by comparing them to production vehicles of a known curb weight and driving range. As one example, the 30 kWh trim of the Nissan Leaf is certified for an EPA range of 107 miles at a curb weight of 1515 kg (3340 lb). This curb weight happens to exactly match the 3340 lb projected curb weight of BEV100 Wt Class 2 (Table 2.113). The projected battery capacity for this vehicle is 27.6 kWh. While this figure is smaller than the 30 kWh capacity of the Leaf, it represents a vehicle with only 100 miles range rather than 107 miles. Also it represents a vehicle with a 20 percent reduction in aerodynamic drag and rolling resistance from a 2008 baseline vehicle. If the production Leaf achieves less reduction than this, it may require a larger battery to achieve its 107 mile range.

A more accurate way to assess the ability of the battery analysis to predict the battery capacity of the Leaf would be to use inputs that represent the actual range of the Leaf. Running the battery sizing methodology with inputs of 107 miles for range and 3340 lb for curb weight results in a prediction of 30.30 kWh, very close to the 30 kWh of the Leaf.

As another example, the Chevy Bolt EV was announced in 2016 as a BEV238 with a curb weight of 3580 lb. Using these as inputs to the battery sizing method, and applying a derate factor of 70 percent (which appears to have been applied to the Bolt for label certification), the result is 61.6 kWh, very close to the 60 kWh of the Bolt. The usable capacity of the Bolt battery remains an uncertainty at this time and represents one variable that could have an impact on the result. While the method assumes a default of 90 percent for BEV200, revising it to 92 percent results in a prediction of 60 kWh.

As a third example, the Tesla Model S P85D weighs 4963 lb and is certified to a label range of 253 miles, using a derate factor of 73.8 percent. The result is 88.75 kWh, quite close to the 85 kWh of this vehicle. Again, the usable capacity of this vehicle is uncertain and could have an impact on the result. A value of 93 percent would predict a capacity of 85 kWh. Also, the AWD configuration of this vehicle is described as having improved efficiency over a single-motor configuration, which might explain the ability of this vehicle to have a smaller battery capacity than the efficiencies encoded into the model would assume.

In similar fashion, modeling the Tesla Model S 60 as a BEV210 at 4323 lb and 79.6 percent derate factor (as certified) results in a prediction of 57.5 kWh, somewhat smaller than the 60 kWh actually provided. Changing the usable capacity to 87 percent, which is in line with various informal estimates for this vehicle, yields 59.5 kWh. Similarly, modeling the Tesla Model S 85 at 265 miles, 4647 lb, and 79.6 percent derate factor yields an estimate of 84 kWh, very close to the actual 85 kWh. Setting the usable capacity to 89 percent would result in a match to 85 kWh.

The 2016 Chevy Volt PHEV achieves an AER of 53 miles at a curb weight of 1607 kg (3543 lb). The Volt usable SOC has been estimated at about 76.1 percent. These inputs result in a prediction of 20.7 kWh, which at first glance is substantially larger than the 18.4 kWh actually provided. However, the method assumes a fairly generous 15 percent oversize factor, which might be different from the factor used by the designers of the Volt. It is also uncertain whether the 76.1 percent usable SOC is assessed at beginning-of-life or end-of-life. Using an oversize factor of about 4 to 5 percent yields a much better match to the actual capacity.

The BMW i3 Rex achieves an AER of 72 miles at a weight of 2982 lb with a 22 kWh battery. Press reports suggest that this vehicle utilizes 87 percent of its battery capacity. Using these inputs results in a prediction of 21 kWh, somewhat smaller than the actual specification but quite close.

The Ford Fusion Energi has a range of 21 miles at 3986 lb using a 7.2 kWh battery. These inputs predict a capacity of 9.0 kWh, a conservative figure. Similarly the Hyundai Sonata PHEV achieves 27 miles at 3810 lb with a 9.8 kWh battery; using these inputs the model would predict a similarly conservative capacity at 11.1 kWh. Particularly for shorter-range PHEVs, it is uncertain whether manufacturer-reported battery capacity figures represent a nameplate capacity at time of manufacture or if the capacity is down-rated to account for actual usable capacity during the life of the vehicle.

By these examples, it is clear that the methodology as revised for this Proposed Determination has greatly improved in its ability to predict battery capacities for xEVs as compared to the version used in the Draft TAR analysis.

It is not to be expected that a single modeling technique with a single set of assumptions will faithfully reproduce the actual battery capacities of all production vehicles. Individual production vehicles are likely to vary in the degree to which the input assumptions of the sizing methodology match those present in the respective vehicles. There could be differences in assumed powertrain efficiencies or differences in application of road load reducing technologies (mass reduction, aerodynamic drag reduction, and rolling resistance reduction) between the production vehicles and the modeled vehicles. For example, if xEV manufacturers are applying more than the 20 percent reduction in aerodynamic drag and rolling resistance (from a baseline vehicle) assumed in the analysis, or are applying more mass reduction, it could result in substantially smaller battery capacity requirements. Also, the larger battery capacity of longer-range BEVs may slightly improve their discharge efficiency relative to shorter range vehicles, because discharge would take place at a lower C rate. Efficiency of regenerative braking might also improve slightly for these vehicles.

Specific examples are valuable in understanding the accuracy of the method, but another perspective can be gained by looking at results in aggregate over a larger population of examples. This can be shown by normalizing the battery capacities of actual and projected vehicles to the corresponding vehicle curb weights, as shown in Figure 2.119 and Figure 2.120. Source data for these Figures are available in the Docket.[616] These comparisons remove the effect of weight differences and more clearly expresses the efficiency with which gross battery capacity is converted to label range for a given vehicle weight.

In Figure 2.119 we compare the battery capacity per unit curb weight (kWh/kg CW) of comparable production BEVs against that of the BEVs modeled in each of 2012 FRM, Draft TAR, and Proposed Determination analyses. For the purpose of this plot, comparable BEVs are defined as BEVs that were available as MY2016-17 vehicles. BEV200+ vehicles that certified for range with a derate factor different from the 75 percent that EPA assumes in this analysis had their range adjusted in the plot to represent what their range would have been had a 75 percent factor been used. With the exception of the Chevy Bolt, these vehicles were Tesla vehicles all of which certified with a derate factor greater than 70 percent.

It can be seen that the revised battery sizing methodology predicts battery capacities for BEVs that follow the trend line established by MY2012-2017 BEVs much more closely than earlier versions of the methodology that were used in the Draft TAR and 2012 FRM. It is also clear that the battery sizing methodology as revised for this Proposed Determination analysis has significantly improved its prediction of BEV battery capacity per unit curb weight compared to the methodology used in either the 2012 FRM analysis or the Draft TAR analysis, both of which generated notably conservative (too large) capacity estimates for BEVs.

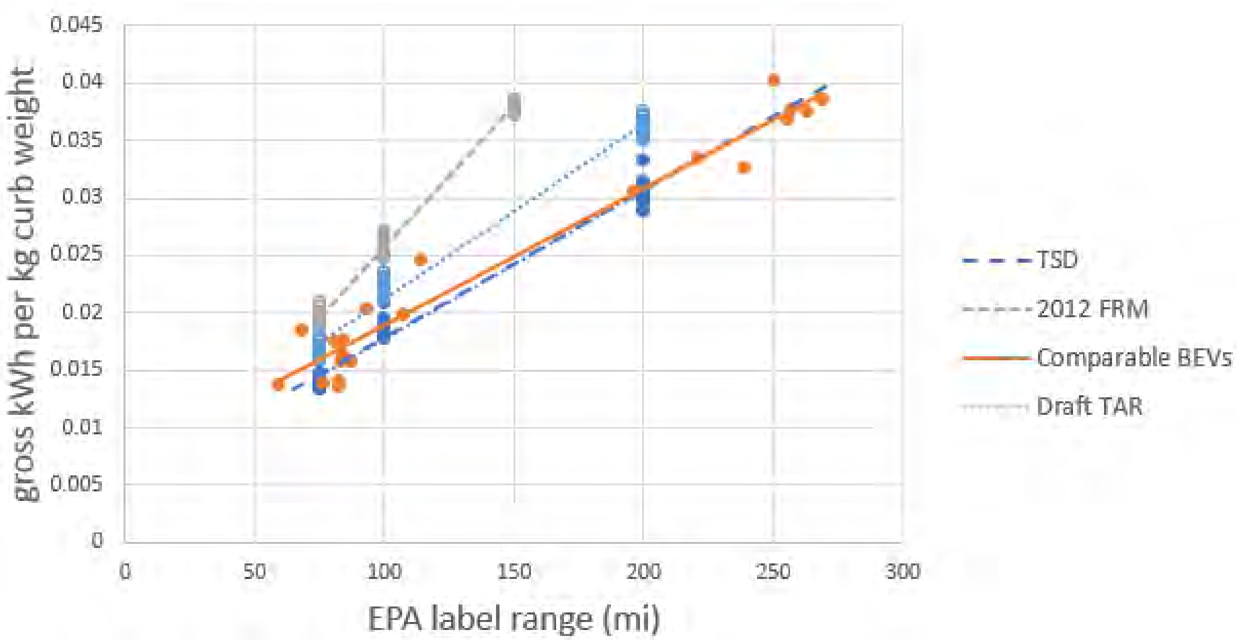


Figure 2.119 Projected BEV Gross Battery Capacity per Unit Curb Weight Compared to Comparable BEVs

For PHEVs, Figure 2.120 performs this comparison for PHEVs. It can be seen that for PHEVs as well, the revised methodology follows the trendline established by production vehicles quite closely, as it did in the Draft TAR analysis, but at a slightly lower position compared to the production vehicle trendline.

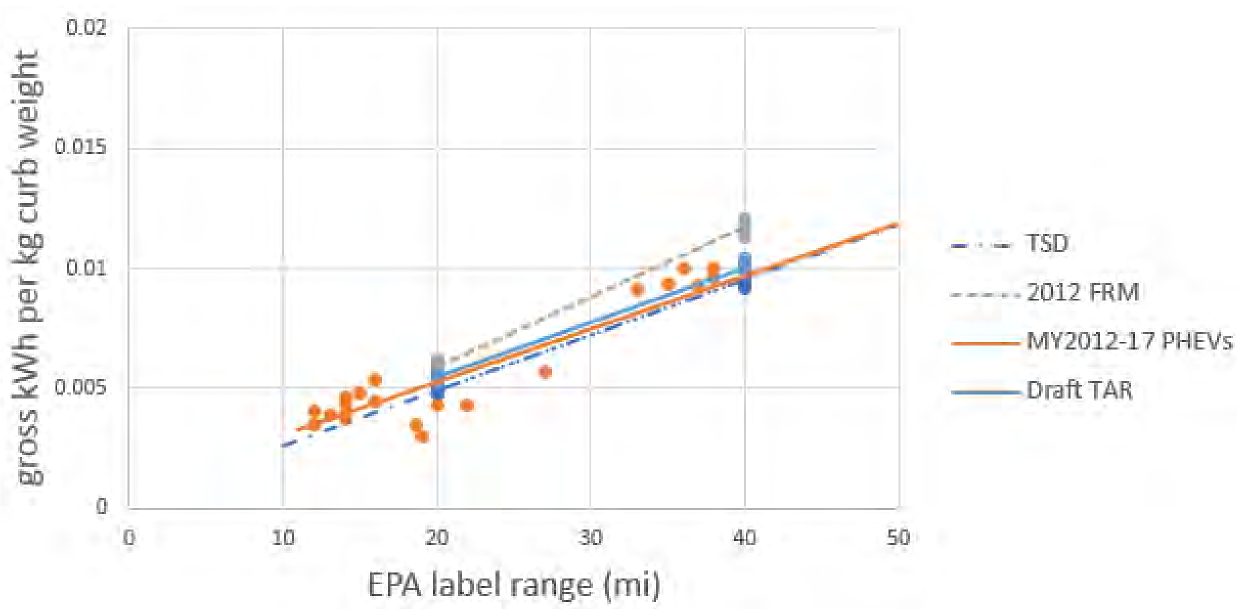


Figure 2.120 Projected PHEV Gross Battery Capacity per Unit Curb Weight Compared To Comparable PHEVs

Particularly for BEVs, the revised method has removed much of the previous tendency to overestimate the gross battery capacity needed to provide a given range for a given curb weight. The revised method creates trendlines for projected BEV and PHEV capacities that follow the respective production-vehicle trendlines quite well, particularly at the BEV200 and PHEV40 points. At shorter range points, such as BEV75, BEV100, and PHEV20, the projected capacity trendlines run slightly below the respective production-vehicle trendlines, indicating that the methodology now projects capacities for these shorter-range vehicles that on average are somewhat smaller than found in MY2012-17 production vehicles. This is consistent with the possibility that shorter-range vehicles, which in the plots consist mostly of relatively low-production examples from a wide variety of manufacturers, may tend to embody a smaller degree of technology optimization than the higher-production examples from a smaller group of relatively well established manufacturers (Tesla and Chevrolet) that dominate the longer range points. In other words, the revised methodology places a slightly greater expectation of future improvement on shorter range vehicles than on longer range vehicles. The fact that real production examples exist that plot on the lower side of both of the projected trendlines (i.e. there are already production examples that convert battery capacity to range more efficiently than the methodology projects for 2025) suggests that the projections are not overly optimistic.

2.3.4.3.7.2 Battery Sizing Methodology for HEVs

HEV battery packs were sized using a simpler methodology described below. This method is continued in the current analysis.

Because there is no "all-electric range" requirement for HEVs, battery pack sizes are relatively consistent for a given weight class. Furthermore, because battery pack sizes are at least an order of magnitude smaller for HEVs than for all-electric vehicles, the sensitivity of HEV vehicle weight (and hence energy consumption) to battery pack size is relatively insignificant. For these reasons, a more direct approach (rather than an iterative process) works for battery sizing of HEVs.

In the Draft TAR analysis as well as this Proposed Determination analysis, HEV batteries were scaled similarly to the 2010 Fusion Hybrid battery, based on a metric of nominal battery energy per pound of equivalent test weight (ETW). Although the Fusion battery utilized a nickel-metal hydride (Ni-MH) chemistry in contrast to the lithium-ion chemistries of the current analysis, the energy window required for hybrid operation and thus gross battery sizing is expected to be similar for either chemistry.

The Fusion Hybrid Ni-MH battery had an ETW ratio of 0.37 Wh/lb. The battery was understood to utilize a 30 percent usable SOC window. The FRM analysis and the current analysis assumes 40 percent for HEVs in the 2020 time frame. The rationale for this assumption is outlined in more detail in Draft TAR Section 5.2.4.4.3. This results in a 25 percent reduction of the energy capacity of the base Fusion battery, or a 0.28 Wh/lb ETW ratio. This value was used to size strong HEV batteries for the analysis.

In comparing anecdotal data for HEVs, EPA assumed a slight weight increase of 4-5 percent for HEVs compared to baseline non-hybridized vehicles. The added weight of the Li-ion pack, motor and other electric hardware were offset partially by the reduced size of the base engine.

2.3.4.3.7.3 ANL BatPaC Battery Design and Cost Model

The U.S. Department of Energy (DOE) has established long term industry goals and targets for advanced battery systems as it does for many energy efficient technologies. Prior to the 2012 FRM, Argonne National Laboratory (ANL) was funded by DOE to provide an independent assessment of Li-ion battery costs because of their expertise in the field as one of the primary DOE National Laboratories responsible for basic and applied battery energy storage technologies for future HEV, PHEV and BEV applications. This led to the development of a Li-ion battery cost model, later named BatPaC.

A basic description of the battery cost model that formed the basis of BatPaC was published in a peer-reviewed technical paper presented at EVS-24.[617] ANL later extended the model to include analysis of manufacturing costs for BEVs and HEVs as well has PHEVs.[618] In early 2011, ANL issued a draft report detailing the methodology, inputs and outputs of their Battery Performance and Cost (BatPaC) model.[619] Soon after, EPA contracted a complete independent peer-review of the BatPaC model and its inputs and results for HEV, PHEV and BEV applications.[620] ANL also provided EPA with an updated report documenting the BatPaC model that fully addressed the issues raised within the peer review.[621] ANL has continued to develop the model on an ongoing basis, adding several new features and refinements to the latest version.[622] For this TSD analysis, EPA used Version 3.0 of BatPaC, which was provided to EPA on December 17, 2015[623] and is the same version used for the Draft TAR analysis.

BatPaC is based on a bill of materials approach in addition to specific design criteria for the intended application of a battery pack. The costs include materials, manufacturing processes, the cost of capital equipment, plant area, and labor for each manufacturing step. The design criteria include detailed parameters such as power and energy storage capacity requirements, cathode and anode chemistry, and the number of cells per module and modules per battery pack. The model assumes use of a stiff-pouch, laminated multi-layer prismatic cell, and battery modules consisting of double-seamed rigid containers. The model supports both liquid-cooling and air-cooling, with appropriate accounting for the resultant structure, volume, cost, and heat rejection capacity of the modules. The model takes into consideration the cost of capital equipment, plant area and labor for each step in the manufacturing process for battery packs and places relevant limits on electrode coating thicknesses and other processes limited by existing and near-term manufacturing processes. The ANL model also takes into consideration annual pack production volume and economies of scale for high-volume production.

EPA chose to adopt the ANL BatPaC model for the following reasons. First, BatPaC has been described and presented in the public domain and does not rely upon confidential business information (which would therefore not be reviewable by the public). The model was developed by scientists at ANL who have significant experience in this area. The model uses a bill of materials methodology which EPA believes is the preferred method for developing cost estimates. BatPaC appropriately considers the target power and energy requirements of the vehicle, which are two of the fundamental parameters when designing a lithium-ion battery for an HEV, PHEV, or BEV. BatPaC can estimate high volume production costs, which EPA believes is appropriate for the 2025 time frame. Finally, its cost estimates are consistent with some of the supplier cost estimates EPA received from large-format lithium-ion battery pack manufacturers. A portion of that data was received from EPA on-site visits to vehicle manufacturers and battery suppliers in 2008.

EPA has worked closely with ANL to test new versions of BatPaC and to guide the development of features that would support the midterm review and this TSD analysis. ANL has since published several iterations of the model that incorporate updated costs, improved costing methods and other improvements.

EPA has also worked closely with ANL to evaluate each successive version of the BatPaC model, to make suggestions for its improvement, and to specifically request features to assist with its use for the purpose of battery costing for the rule. EPA also worked with ANL to arrange for an independent peer review of the model in 2011. This peer review along with EPA input led to many improvements that were described in the TSD that accompanied the 2012 FRM. ANL has continued to make improvements and add new features since the FRM, many at EPA request. Recent development has included: support for additional battery module topologies, improved modeling of impedance and electrode thickness, improved evaluation of battery thermal capabilities, revised electrode chemistries such as NMC622, improved accounting for plant costs and overhead, improved cost accounting for solvent recovery, customization of cell thickness parameters, generation of USABC parameters, and updated costs for all constituent cell materials.

To conduct the Draft TAR analysis, in December 2015 ANL provided EPA with a beta copy of BatPaC Version 3. After testing and evaluation, this version was used in the Draft TAR GHG Assessment, and continues to be used for this Proposed Determination assessment. A copy of this file is available in Docket EPA-HQ-OAR-2015-0827.

Basic user inputs to BatPaC include performance goals (power and energy capacity), choice of battery chemistry (of several predefined chemistries), the vehicle type for which the battery is intended (HEV, PHEV, or BEV), the desired number of cells and modules and their layout in the pack, and the volume of production. BatPaC then designs the electrodes, cells, modules, and battery pack, and provides a complete, itemized cost breakdown at the specified production volume.

BatPaC provides default values for engineering properties and material costs that allow the model to operate without requiring the user to supply detailed technical or experimental data. In general, the default properties and costs represent what the model authors consider to be reasonable values representing the state of the art expected to be available to large battery manufacturers in the year 2020. Users are able to edit these values as necessary to represent their own expectations or their own proprietary data.

In using BatPaC, it is extremely important that the user monitor certain properties of the cells, modules, and packs that it generates, to ensure that they stay within practical design guidelines, adjusting related inputs if necessary. In particular, pack voltage and individual cell capacity should be limited to appropriate ranges for the application. These design guidelines are not rigidly defined, but approximate ranges are beginning to emerge in the industry.

The cost outputs used by EPA to determine 2025 HEV, PHEV and BEV battery costs were based on the inputs and assumptions described in the next section. For engineering properties and material costs, and for other parameters not identified below, EPA used the defaults provided in the model.

2.3.4.3.7.4 Assumptions and Inputs to BatPaC

After considering applicable public comments and updated information, EPA chose basic user inputs to BatPaC as follows.

For performance goals, EPA used the power and energy requirements derived from the battery sizing analysis described in the previous section. Additional inputs include battery chemistry, vehicle type (BEV, PHEV, or HEV), cell and module layout, and production volumes, as outlined below.

In addition to these inputs, EPA monitored certain outputs to ensure that the resultant cell and pack specifications were realistic. In particular, pack voltages, electrode dimensions, cooling capability, and individual cell capacities were monitored to ensure that they were consistent with current and anticipated industry practice.

Additionally, EPA did not include warranty costs computed by BatPaC in the total battery cost because these are accounted for elsewhere in the analysis by means of indirect cost multipliers (ICMs).

<u>Battery chemistry</u>

Chemistries were chosen due to their known characteristics and to be consistent with both publicly available information on current and near term HEV, PHEV and BEV product offerings from OEMs.

In both the Draft TAR and this Proposed Determination analysis, EPA selected NMC622 for BEV and PHEV40 packs, and a blended cathode (25 percent NMC and 75 percent LMO, the BatPaC default value) for PHEV20 and HEV packs. As discussed in the Draft TAR, although most current Li-Ion HEV packs are reported to be using NMC cathodes,[624] EPA used a blended cathode for HEV batteries because the default NMC formulations modeled by BatPaC do not support the high power-to-energy ratios required by some of the modeled HEV configurations. In August 2016, EPA coordinated with ANL for an update to the BatPaC NMC formulation that would allow HEV packs to be constructed with NMC cathodes. ANL recommended certain changes to input parameters that enabled higher power for these batteries. However, since the costs of HEV packs with NMC cathodes generated by this technique did not differ significantly from those with blended cathodes, EPA ultimately decided to continue using blended cathodes for HEV batteries.

Pack topology and cell capacity

In the Draft TAR analysis, EPA optimized the pack topology for BEVs and PHEVs by choosing values for cells per module and number of modules to target a preferred cell capacity. This practice continues for this Proposed Determination analysis. Since the number of modules per pack must be a whole number, varying the number of cells per module allows the number of cells per pack and their capacities to be better targeted. In the Draft TAR, EPA varied the number of cells per module to between 24 and 36. This was revised to between 20 and 36 for this Proposed Determination analysis in order to better target pack voltages and maximum cell capacities.

In public comments on the Draft TAR, Toyota stated: "As noted, the Draft TAR explains that the ideal number of cells per module may vary depending on the capacity of the pack and the size of the cells and it may be more appropriate to optimize the pack topology by varying the number of cells per module in order to better match performance targets and minimize cost. However, Toyota does not share this perspective as an increase in capacity does not necessarily mean that the number of cells can be reduced. Reduction of cells number causes voltage decrease and current increase. So the numbers of cells cannot be reduced by a certain degree."

To clarify, the EPA battery analysis does not reduce the number of cells per pack as battery capacity increases. Pack voltages are always targeted to a range between about 300 to 400 volts. As pack capacity increases, the number of cells may also increase, as might the capacity of each cell and the number of parallel cells. In general, if a smaller number of cells per module is specified in order to stay within cell capacity and pack voltage targets, there will be a larger number of modules to compensate and voltage will therefore not decrease. Detailed information regarding the specific topology of each of the 150 PEV battery packs modeled in the analysis are contained in the EPA Battery Analysis (Proposed Determination) Spreadsheets which are available in the Docket.

In the Draft TAR, EPA targeted an individual cell capacity of 60 A-hr for BEV packs (not to exceed 75 A-hr) and 45 A-hr for PHEV packs (not to exceed 50 A-hr). This was based in part on examples seen in the industry, such as the 55 Ampere-hour cells that appear to be used by Nissan and GM in their recently announced 60-kWh packs, and larger cell sizes currently produced or recently announced by leading suppliers.

Since the Draft TAR was completed, at least one additional example of a significantly larger cell size has appeared in a production BEV. The BMW i3 94 Ah uses a 94 Ampere-hour cell, which is significantly larger than most other manufacturers have been using. Because this vehicle has now entered the market and has effectively replaced the 60 A-hr version, it provides additional evidence that cells of this capacity can be effective in a BEV application. Accordingly, EPA has updated the limits on maximum cell capacity for this Proposed Determination analysis. BEV cells are now allowed to reach a maximum of approximately 90 A-hr. In most cases, it is only the longer range BEVs that approach this limit. For vehicles that approach the limit, the use of these larger cells tends to reduce pack costs by tending toward smaller numbers of cells of a larger capacity than might have been applicable in the Draft TAR analysis. HEV packs, which consist of a single module, are configured with 32 cells as before.

Thermal management

In the Draft TAR analysis, all BEV, PHEV, and HEV packs were modeled with liquid cooling as defined by the BatPaC model.

As before, BatPaC continues to provide an option for active air cooling in which individual cells are separated by air passages through which cabin air or cooled air is circulated. Use of this option results in package volumes that are much larger than for a liquid cooled pack. As described in the Draft TAR, although passive air cooling continues to be prevalent in HEV packs at the time of this writing, some industry sources have indicated that liquid cooling may also be preferable for HEV packs in order to improve utilization of capacity and increase service life. Minimization of under-hood package volume is also a growing concern. As in the Draft TAR analysis, EPA therefore chose to utilize liquid cooling for HEV packs as well as for BEV and PHEV packs for this Proposed Determination analysis.

Pack voltage

As in the Draft TAR analysis, for this Proposed Determination analysis, EPA limited BEV and PHEV voltages to approximately 120V for HEVs (except 48V HEVs) and approximately 300-400V for BEVs and PHEVs.

In public comments on the Draft TAR, Toyota commented, "Toyota does not understand why HEV voltage remains at 120V." In response, although it is true that some mild and strong HEVs are currently targeting voltage ranges higher than 120V, the systems on which EPA based its teardown-derived costs were systems that operated in the 120V range. There are likely to be some advantages to operating at a higher voltage. However, increasing the voltage of a small (approximately 1 kWh) pack to several hundred volts requires a relatively large number of relatively small cells, at a potentially higher cost due to the larger number of cells and cell connections. Going forward to the 2022 to 2025 time frame, it is unclear whether the advantage of operating an HEV at a higher voltage will continue to outweigh the higher cost of the battery.

Toyota also noted, "The Draft TAR's assessment that the customary voltage range for a given xEV category is an outgrowth of the relative size of the battery is incorrect. The voltage is not a by-product but a crucial speciation necessary in determining the output of the battery." EPA has clarified the text in the corresponding section.

Toyota also stated, "The Draft TAR provides examples of PHEVs and BEVs in the 600V range … However, Toyota finds that the increase in voltage does not always necessarily lead to an increase in performance. Consequently, the cost of each of the components may increase, and the efficiency sometimes degrades." EPA acknowledges the comment, and reiterates that in both the Draft TAR and this Proposed Determination analyses, voltages in the modeled PEVs are limited to between approximately 300V and 400V.

Electrode dimensions

For electrode coating thickness, the 100-micron maximum limit used in the Draft TAR analysis is retained in this Proposed Determination analysis.

In the Draft TAR it was noted that recent developments in pack design (as described in Draft TAR Section 5.2.4.4.6, Electrode Dimensions) suggest that the industry may be moving toward low-profile or flat floor-mounted packs. For this reason, the Draft TAR analysis adopted the BatPaC default aspect ratio of 3:1. This aspect ratio continues to be used in this Proposed Determination analysis.

Manufacturing volumes

For this Proposed Determination analysis, the assumed manufacturing volume for BEV, PHEV and HEV battery packs was retained at 450,000 per year as in the Draft TAR analysis. For additional discussion of considerations with regard to the assumed manufacturing volume, please refer to Chapter 2.2.4.5.7 (Pack Manufacturing Volumes) of this TSD.

In comments on the Draft TAR, Global Automakers commented on the role of production volume in achieving economies of scale: "the agencies considered a volume of 450,000 units necessary to achieve full economies of scale. In its 2015 study, the NRC noted that the technology penetration levels projected by the agencies did not reach that level, and that no one manufacturer would reach that level. In the TAR, the agencies respond that economies of scale can be obtained at levels as low as 60,000, and put forward a number of other arguments on battery costs. Nonetheless, it cannot be denied that at current sales levels of electric-drive vehicles of less than one percent (1 percent) of the market (i.e., less than 17,000 vehicles), manufacturers are not close to volumes that could provide economies of scale. Unless demand for those vehicles increases dramatically, economies of scale will remain out of reach."

EPA acknowledges that electrified vehicle sales are not currently approaching the 450,000 units per year assumed in the Draft TAR analysis. However, evidence continues to grow that the battery costs projected by the EPA analysis may be conservative nonetheless. As discussed in the Draft TAR, the GM/LG cost disclosure provides some evidence that battery costs may already be approaching the costs projected by the EPA analysis at volumes much lower than 450,000, given that the disclosed battery costs for the Bolt are likely to be predicated on a much lower annual production volume. When taken in light of other comments received on the Draft TAR that characterize the projected costs as already conservative, reducing the production volume as an input to BatPaC and thereby increasing projected costs would seem to be unwarranted. It also would presuppose that electrified vehicle sales will fail to grow significantly in the future, something which is not at all certain despite the low penetration levels projected for compliance with this rule. It remains the position of some commenters that electric vehicle sales are poised for significant growth for reasons that go well beyond regulatory influences. As Faraday Future commented, "notwithstanding today's low gasoline prices, the number of electric vehicles on the roads in the United States is going to climb, and climb steeply between now and 2022," and went on to point out that "there are also many recent publications that analyze the factors above and recent data to project EV penetration rates that far exceed those assumed in the Draft TAR." The recent sales growth in Tesla vehicles, the large number of reservations for the Model 3, and Tesla's plans for rapid expansion also suggest that at least some stakeholders are taking a strong position that the 450,000 vehicles per year on which the EPA battery cost assumptions are nominally based is an attainable outcome.

Summary of Battery Design Assumptions

Table 2.115 shows a summary of battery design assumptions used in the Draft TAR analysis and those adopted for this Proposed Determination analysis.

Table 2.115 Battery Design Assumptions Input to BatPaC and Changes from Draft TAR to Proposed Determination

Assumption	Draft TAR	**Proposed Determination**
BEV75 chemistry	NMC622-G	unchanged
BEV100 chemistry	NMC622-G	unchanged
BEV150/200 chemistry	NMC622-G	unchanged
PHEV20 chemistry	25%NMC/75%LMO-G	unchanged
PHEV40 chemistry	NMC622-G	unchanged
HEV chemistry	25%NMC/75%LMO-G	unchanged
Pack topology	optimized to target preferred cell capacity	unchanged
Maximum cell capacity (A-hr)	BEV: target 60, max 75 PHEV: target 45, max 50	**BEV: max 90** **PHEV: max 60**
Cells per module	24 to 32	unchanged
BEV thermal medium	Liquid	unchanged
PHEV thermal medium	Liquid	unchanged
HEV thermal medium	Liquid	unchanged
BEV pack voltage range (V)	300V to 400V	unchanged
PHEV pack voltage range (V)	300V to 400V	unchanged
HEV pack voltage range (v)	~120V	unchanged
Maximum electrode thickness (microns)	100	unchanged
Electrode aspect ratio	3:1	unchanged
BEV battery 2025 annual mfg volume	450,000	unchanged
PHEV battery 2025 annual mfg volume	450,000	unchanged
HEV battery 2025 annual mfg volume	450,000	unchanged

2.3.4.3.7.5 Battery Cost Projections for xEVs

In Table 2.117 through Table 2.122 we show the battery pack direct manufacturing costs (DMC) that were generated by the EPA battery analysis workbooks[601] for this Proposed Determination. The average degree of change from cost generated for the Draft TAR is also shown, for each level of applied mass reduction technology. The costs are quoted in 2015 dollars and the analysis assigns them to the year 2025 for BEVs and PHEVs and the year 2017 for HEVs. This assignment follows the convention used in previous analysis for the 2012 FRM and Draft TAR, where HEV battery costs were assigned to the earlier year to reflect considerations such as the relatively larger number of HEV batteries that were in production relative to PHEV and BEV batteries.

As in the Draft TAR, the costs shown are BatPaC output figures minus warranty costs. The warranty costs computed by BatPaC are subtracted because the EPA analysis accounts for warranty costs by means of indirect cost multipliers (ICMs).

It is important to understand that the figures shown in Table 2.117 through Table 2.122 should not necessarily be understood as predictions of future battery costs for any specific future electrified vehicles. Rather, these figures are BatPaC outputs that serve as input data points for the generation of cost curves that the OMEGA model uses to estimate battery costs for the electrified vehicles generated by OMEGA for each year of the rule. Only the electrified vehicles generated by OMEGA, and not the electrified vehicles modeled in the EPA battery analysis workbooks to generate the input data points, figure into the compliance analysis. The vehicles described in the battery analysis workbooks can, however, be useful to understand other assumptions pertinent to the analysis, such as for example, the amount of battery capacity that is estimated to be needed to provide a given driving range for a given curb weight, or the pack topologies and cell sizes assumed to be applicable to these vehicles. It should be understood, however, that the specific configurations modeled in the workbooks do not necessarily constitute predictions of any specific future vehicles.

As mentioned above, one of the ways EPA uses these BatPaC workbook figures is to generate learning curves that assign battery costs to each individual year over the full time frame of the rule. This curve is developed by first considering the BatPaC costs as applicable to the 2025 MY for BEVs and PHEVs and to the 2017 MY for HEVs. EPA then used this curve to "unlearn" those costs back to the present year. This allows EPA to estimate costs applicable to MYs 2017 through 2025, which are reported in Table 2.126 through Table 2.131. The changes in direct manufacturing costs from year-to-year therefore reflect cost changes due to learning effects. Learning curves were developed as described in Chapter 2.3.2.1.4.

As shown in Table 2.116, projected battery pack costs for many electrified vehicle configurations have fallen substantially from those projected in the Draft TAR analysis. These changes are the result of many influences, but are primarily due to projection of smaller pack capacities for a given range target, and larger cell capacities within each pack. The change in cost per kWh is not as great because most of these changes have a stronger effect on total pack cost rather than cost per kWh. In some cases, potential reductions in cost per kWh resulting from, for example, larger cell sizes, were offset by other adjustments, such as oversizing of PHEV batteries to account for range degradation.

Table 2.116 Average Change in Projected Battery Pack DMC from Draft TAR to Proposed Determination

Electrified Vehicle Type	Average change	
	Change in pack cost	Change in cost per kWh
BEV75	-11.9%	+3.4%
BEV100	-13.6%	+1.6%

BEV200	-18.3%	+3.7%
PHEV40	-5.0%	-2.2%
PHEV20	-4.2%	+4.3%
HEV	+0.8%	-2.0%

The Proposed Determination battery costs are not directly comparable to those of the Draft TAR analysis because of the change in LPM class definitions, which means that vehicles in each of the six classes have different curb weights and power requirements. However, costs can be compared on an average basis across all classes. Compared to the Draft TAR, costs for BEV75 and BEV100 have fallen by an average of about 12 to 14 percent on a total pack cost basis. BEV200 pack costs fell by an average of about 18 percent, reflecting the larger net pack size reductions for these larger, longer-range packs. On a cost per kWh basis, costs for BEVs rose by about 1.5 to 3.5 percent (due largely to the increase in power-to-energy ratio resulting from reductions in pack capacity while power requirements remained relatively unchanged). The dominant factor in reduction of total pack costs for BEVs was the reduction in projected pack capacities for a given range.

PHEV40 and PHEV20 battery pack costs have fallen by about 4 to 5 percent, having benefited from forces similar to those that have reduced BEV costs. The cost reductions were not as great as for BEVs because the updated Proposed Determination analysis imposes a battery oversizing factor to account for PHEV range degradation.

HEV costs have remained similar to those of the Draft TAR. This is due to few if any changes to the modeling methodology and assumptions applicable to HEVs. The primary cause of any changes would be due to the change in LPM class definitions, which changed the curb weight and power demand for each vehicle class.

It should be noted that BatPaC does not model passively air cooled HEV cell assemblies (that is, without significant air flow passages between the cells). A passively cooled assembly without integrated air passages would probably have a lower cost than other available options. However, as modeled by BatPaC, liquid cooled HEV packs have a slightly lower cost than the available air cooled options, and for this reason as well as the expectation that liquid cooling will enable better capacity utilization, EPA chose liquid cooling for HEV packs

Table 2.117 Estimated Direct Manufacturing Costs in MY2025 for BEV75 Battery Packs

BEV75* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$3,962	$203	$3,940	$205	$3,893	$208	$3,873	$210	$3,788	$219
Standard Car	$4,411	$184	$4,391	$186	$4,331	$189	$4,308	$190	$4,203	$196
Large Car	$5,807	$192	$5,752	$193	$5,603	$193	$5,538	$194	$5,404	$195
Small MPV	$4,514	$177	$4,489	$179	$4,431	$182	$4,406	$183	$4,301	$189
Large MPV	$5,380	$164	$5,351	$165	$5,278	$168	$5,248	$169	$5,121	$175

Truck	$5,856	$157	$5,805	$158	$5,674	$159	$5,614	$159	$5,457	$165
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$3,819	$205	$3,800	$207	$3,750	$211	$3,769	$216	$3,660	$223
Wt Class 2	$3,989	$193	$3,965	$195	$3,900	$200	$3,870	$202	$3,762	$211
Wt Class 3	$4,099	$186	$4,071	$188	$3,994	$193	$3,962	$195	$3,837	$205
Wt Class 4	$4,332	$176	$4,309	$178	$4,248	$186	$4,223	$189	$4,135	$204
Wt Class 5	$4,912	$160	$4,832	$161	$4,760	$171	$4,654	$173	$4,520	$189
Wt Class 6	$4,997	$162	$4,985	$166	$4,853	$174	$4,746	$176	$4,620	$193
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	-3.6%	1.0%	-3.6%	1.1%	-3.7%	1.4%	-2.7%	2.8%	-3.4%	1.7%
Wt Class 2	-9.6%	4.6%	-9.7%	4.8%	-10.0%	5.7%	-10.2%	6.2%	-10.5%	7.5%
Wt Class 3	-29.4%	-3.4%	-29.2%	-2.6%	-28.7%	-0.3%	-28.5%	0.9%	-29.0%	5.3%
Wt Class 4	-4.0%	-0.9%	-4.0%	-0.1%	-4.1%	2.3%	-4.2%	3.5%	-3.8%	7.9%
Wt Class 5	-8.7%	-2.8%	-9.7%	-2.4%	-9.8%	1.7%	-11.3%	2.0%	-11.7%	8.3%
Wt Class 6	-14.7%	2.9%	-14.1%	5.2%	-14.5%	9.3%	-15.5%	10.2%	-15.3%	16.9%
AVE CHANGE	**-11.7%**	**0.2%**	**-11.7%**	**1.0%**	**-11.8%**	**3.4%**	**-12.0%**	**4.3%**	**-12.3%**	**7.9%**

Note:

CWR = target percent reduction in vehicle curb weight.

Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.

*NMC622 cathode.

Table 2.118 Estimated Direct Manufacturing Costs in MY2025 for BEV100 Battery Packs

BEV100* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$4,533	$175	$4,511	$176	$4,450	$179	$4,428	$180	$4,345	$185
Standard Car	$5,306	$166	$5,278	$167	$5,207	$170	$5,179	$171	$5,095	$175
Large Car	$6,476	$161	$6,417	$161	$6,265	$162	$6,197	$162	$6,122	$164
Small MPV	$5,404	$159	$5,374	$160	$5,342	$164	$5,312	$165	$5,223	$169
Large MPV	$6,266	$144	$6,227	$144	$6,139	$147	$6,102	$148	$5,995	$151
Truck	$6,266	$135	$6,227	$135	$6,139	$137	$6,102	$138	$5,995	$142
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$4,296	$173	$4,273	$175	$4,211	$178	$4,183	$180	$4,087	$185
Wt Class 2	$4,547	$165	$4,477	$165	$4,395	$169	$4,359	$171	$4,235	$177
Wt Class 3	$4,693	$159	$4,657	$161	$4,555	$165	$4,471	$165	$4,330	$172
Wt Class 4	$5,079	$155	$4,946	$154	$4,830	$159	$4,724	$159	$4,500	$165
Wt Class 5	$5,998	$146	$5,924	$148	$5,728	$154	$5,234	$146	$5,022	$155
Wt Class 6	$6,009	$146	$5,935	$148	$5,763	$155	$5,315	$148	$5,107	$157
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	-5.2%	-0.7%	-5.3%	-0.7%	-5.4%	-0.4%	-5.5%	-0.2%	-5.9%	0.4%
Wt Class 2	-14.3%	-0.9%	-15.2%	-1.6%	-15.6%	-0.9%	-15.8%	-0.5%	-16.9%	1.1%
Wt Class 3	-27.5%	-0.8%	-27.4%	-0.1%	-27.3%	1.7%	-27.8%	1.8%	-29.3%	5.4%
Wt Class 4	-6.0%	-3.0%	-8.0%	-4.2%	-9.6%	-3.5%	-11.1%	-4.0%	-13.9%	-2.4%
Wt Class 5	-4.3%	1.9%	-4.9%	2.8%	-6.7%	5.2%	-14.2%	-1.3%	-16.2%	2.9%
Wt Class 6	-9.9%	8.6%	-10.5%	9.6%	-11.8%	12.8%	-18.1%	6.8%	-19.3%	10.8%
AVE CHANGE	**-11.2%**	**0.9%**	**-11.9%**	**1.0%**	**-12.7%**	**2.5%**	**-15.4%**	**0.4%**	**-16.9%**	**3.0%**

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 2.119 Estimated Direct Manufacturing Costs in MY2025 for BEV200 Battery Packs

BEV200* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$6,712	$156	$6,675	$157	$6,588	$160	$6,572	$161	$6,588	$160
Standard Car	$7,394	$140	$7,351	$141	$7,246	$143	$7,224	$144	$7,224	$144
Large Car	$8,851	$133	$8,797	$134	$8,743	$134	$8,743	$134	$8,743	$134
Small MPV	$7,734	$138	$7,688	$139	$7,555	$141	$7,555	$141	$7,555	$141
Large MPV	$9,160	$127	$9,101	$128	$8,966	$130	$8,966	$130	$8,966	$130
Truck	$9,795	$119	$9,732	$120	$9,579	$122	$9,515	$123	$9,515	$123
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$5,932	$145	$5,896	$146	$5,802	$148	$5,760	$149	$5,716	$151
Wt Class 2	$6,255	$137	$6,208	$138	$6,083	$141	$6,027	$142	$5,963	$144
Wt Class 3	$6,460	$133	$6,407	$134	$6,261	$137	$6,196	$138	$6,119	$140
Wt Class 4	$6,846	$126	$6,776	$127	$6,589	$131	$6,507	$132	$6,403	$134
Wt Class 5	$7,828	$115	$7,717	$117	$7,477	$122	$7,187	$121	$7,051	$124
Wt Class 6	$7,841	$115	$7,730	$117	$7,434	$121	$7,310	$123	$7,005	$120
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	-11.6%	-7.5%	-11.7%	-7.5%	-11.9%	-7.4%	-12.4%	-7.0%	-13.2%	-5.8%
Wt Class 2	-15.4%	-2.3%	-15.6%	-2.1%	-16.0%	-1.6%	-16.6%	-0.9%	-17.5%	0.3%
Wt Class 3	-27.0%	-0.2%	-27.2%	0.1%	-28.4%	1.9%	-29.1%	3.0%	-30.0%	4.4%
Wt Class 4	-11.5%	-8.8%	-11.9%	-8.4%	-12.8%	-7.1%	-13.9%	-5.9%	-15.3%	-4.4%
Wt Class 5	-14.5%	-9.2%	-15.2%	-8.5%	-16.6%	-6.1%	-19.8%	-6.8%	-21.4%	-4.2%
Wt Class 6	-19.9%	-3.6%	-20.6%	-2.9%	-22.4%	-0.9%	-23.2%	0.0%	-26.4%	-2.4%
AVE CHANGE	**-16.7%**	**-5.3%**	**-17.0%**	**-4.9%**	**-18.0%**	**-3.5%**	**-19.2%**	**-2.9%**	**-20.6%**	**-2.0%**

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 2.120 Estimated Direct Manufacturing Costs in MY2025 for PHEV20 Battery Packs

PHEV20* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$2,463	$382	$2,454	$385	$2,433	$394	$2,424	$397	$2,420	$399
Standard Car	$2,690	$340	$2,678	$342	$2,649	$349	$2,638	$352	$2,638	$352
Large Car	$3,157	$316	$3,136	$318	$3,080	$321	$3,070	$322	$3,070	$322
Small MPV	$2,737	$325	$2,727	$328	$2,699	$335	$2,688	$337	$2,683	$339
Large MPV	$3,025	$279	$3,008	$281	$2,962	$285	$2,942	$287	$2,937	$288
Truck	$3,190	$259	$3,169	$261	$3,115	$264	$3,103	$265	$3,103	$265
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$2,448	$371	$2,439	$374	$2,415	$383	$2,404	$387	$2,403	$388
Wt Class 2	$2,589	$352	$2,576	$356	$2,490	$359	$2,478	$364	$2,476	$365
Wt Class 3	$2,643	$337	$2,629	$341	$2,601	$354	$2,591	$360	$2,589	$361
Wt Class 4	$2,791	$319	$2,779	$324	$2,749	$339	$2,737	$345	$2,735	$346
Wt Class 5	$3,025	$277	$3,006	$283	$2,958	$299	$2,937	$307	$2,932	$309
Wt Class 6	$3,017	$275	$2,998	$281	$2,950	$298	$2,930	$305	$2,927	$307
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	-0.6%	-3.0%	-0.6%	-3.0%	-0.7%	-2.7%	-0.8%	-2.5%	-0.7%	-2.8%
Wt Class 2	-3.8%	3.6%	-3.8%	4.0%	-6.0%	2.8%	-6.1%	3.4%	-6.1%	3.7%
Wt Class 3	-16.3%	6.7%	-16.2%	7.4%	-15.5%	10.0%	-15.6%	11.6%	-15.7%	12.0%
Wt Class 4	1.9%	-2.0%	1.9%	-1.2%	1.9%	1.2%	1.8%	2.4%	2.0%	2.2%
Wt Class 5	0.0%	-0.9%	-0.1%	0.5%	-0.1%	4.8%	-0.2%	6.9%	-0.2%	7.2%
Wt Class 6	-5.4%	6.2%	-5.4%	7.9%	-5.3%	12.7%	-5.6%	15.4%	-5.7%	15.9%
AVE CHANGE	**-4.0%**	**1.7%**	**-4.0%**	**2.6%**	**-4.3%**	**4.8%**	**-4.4%**	**6.2%**	**-4.4%**	**6.4%**

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*Blended LMO-NMC cathode.

Table 2.121 Estimated Direct Manufacturing Costs in MY2025 for PHEV40 Battery Packs

PHEV40* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$3,130	$260	$3,111	$262	$3,077	$264	$3,078	$264	$3,077	$264
Standard Car	$3,705	$251	$3,599	$246	$3,559	$247	$3,559	$247	$3,559	$247
Large Car	$5,528	$295	$5,550	$296	$5,552	$296	$5,550	$296	$5,552	$296
Small MPV	$3,661	$233	$3,635	$234	$3,579	$236	$3,579	$236	$3,579	$236
Large MPV	$4,620	$229	$4,622	$231	$4,574	$232	$4,574	$232	$4,574	$232
Truck	$5,073	$221	$5,026	$221	$4,999	$222	$4,999	$222	$4,999	$222
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$3,223	$250	$3,215	$253	$3,198	$258	$3,198	$258	$3,198	$258
Wt Class 2	$3,468	$242	$3,457	$245	$3,438	$251	$3,438	$251	$3,438	$251
Wt Class 3	$3,614	$237	$3,601	$240	$3,579	$247	$3,579	$247	$3,579	$247
Wt Class 4	$3,935	$232	$3,991	$239	$3,973	$246	$3,973	$246	$3,973	$246
Wt Class 5	$4,837	$227	$4,814	$232	$4,375	$222	$4,432	$224	$4,778	$241
Wt Class 6	$4,936	$231	$4,914	$237	$4,378	$221	$4,543	$228	$4,887	$244
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	3.0%	-3.8%	3.3%	-3.3%	3.9%	-1.9%	3.9%	-1.9%	3.9%	-1.9%
Wt Class 2	-6.4%	-3.4%	-3.9%	-0.5%	-3.4%	1.9%	-3.4%	1.9%	-3.4%	1.9%
Wt Class 3	-34.6%	-19.7%	-35.1%	-18.9%	-35.5%	-16.6%	-35.5%	-16.5%	-35.5%	-16.6%
Wt Class 4	7.5%	-0.3%	9.8%	2.0%	11.0%	3.9%	11.0%	3.9%	11.0%	3.9%
Wt Class 5	4.7%	-0.6%	4.1%	0.4%	-4.3%	-4.4%	-3.1%	-3.2%	4.5%	4.0%
Wt Class 6	-2.7%	4.7%	-2.2%	6.8%	-12.4%	-0.3%	-9.1%	2.8%	-2.2%	10.1%
AVE CHANGE	-4.8%	-3.8%	-4.0%	-2.3%	-6.8%	-2.9%	-6.0%	-2.2%	-3.6%	0.2%

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*NMC622 cathode.

Table 2.122 Estimated Direct Manufacturing Costs in MY2017 for strong HEV Battery Packs

STRONG HEV* (450k/yr)	0% CWR		2% CWR		7.5% CWR		10% CWR		20% CWR	
Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Small Car	$ 984	$ 1,216	$ 980	$ 1,236	$ 971	$ 1,297	$ 966	$1,326	$ 958	$ 1,383
Standard Car	$ 1,051	$ 1,057	$ 1,046	$ 1,074	$ 1,033	$ 1,123	$ 1,027	$1,148	$ 1,016	$ 1,198
Large Car	$ 1,197	$ 976	$ 1,188	$ 988	$ 1,168	$ 1,029	$ 1,158	$1,050	$ 1,140	$ 1,093
Small MPV	$ 1,033	$ 984	$ 1,029	$ 1,000	$ 1,017	$ 1,047	$ 1,011	$1,070	$ 1,001	$ 1,118
Large MPV	$ 1,123	$ 855	$ 1,117	$ 868	$ 1,100	$ 907	$ 1,093	$ 925	$ 1,078	$ 966
Truck	$ 1,194	$ 792	$ 1,187	$ 803	$ 1,167	$ 836	$ 1,158	$ 853	$ 1,142	$ 882
Proposed Determination										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	$1,001	$1,144	$998	$1,161	$986	$1,209	$982	$1,234	$972	$1,298
Wt Class 2	$1,046	$1,041	$1,042	$1,056	$1,030	$1,101	$1,025	$1,123	$1,012	$1,180
Wt Class 3	$1,069	$989	$1,063	$1,002	$1,050	$1,044	$1,044	$1,064	$1,030	$1,118
Wt Class 4	$1,122	$931	$1,116	$944	$1,101	$983	$1,094	$1,001	$1,077	$1,051
Wt Class 5	$1,182	$823	$1,176	$834	$1,157	$867	$1,149	$883	$1,127	$924
Wt Class 6	$1,196	$831	$1,189	$842	$1,170	$875	$1,162	$891	$1,144	$926
Change from Draft TAR										
	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh	Pack	$/kWh
Wt Class 1	1.8%	-5.9%	1.8%	-6.1%	1.6%	-6.7%	1.6%	-7.0%	1.4%	-6.2%
Wt Class 2	-0.4%	-1.5%	-0.4%	-1.7%	-0.3%	-2.0%	-0.2%	-2.2%	-0.4%	-1.5%
Wt Class 3	-10.7%	1.3%	-10.5%	1.3%	-10.1%	1.4%	-9.8%	1.4%	-9.6%	2.4%
Wt Class 4	8.6%	-5.4%	8.5%	-5.6%	8.3%	-6.1%	8.2%	-6.4%	7.7%	-6.0%
Wt Class 5	5.3%	-3.8%	5.3%	-4.0%	5.2%	-4.4%	5.2%	-4.6%	4.6%	-4.4%
Wt Class 6	0.2%	5.0%	0.2%	4.9%	0.3%	4.6%	0.3%	4.5%	0.2%	4.9%
AVE CHANGE	**0.8%**	**-1.7%**	**0.8%**	**-1.8%**	**0.8%**	**-2.2%**	**0.9%**	**-2.4%**	**0.6%**	**-1.8%**

Note:

CWR = target percent reduction in vehicle curb weight.
Actual reduction will be less if it would require applying more than 20 percent mass reduction to glider.
*Blended LMO-NMC cathode.

2.3.4.3.7.6 Discussion of Battery Cost Projections

In Draft TAR Section 5.2.4.4.9 (Evaluation of 2012 FRM Battery Cost Projections), EPA reviewed the 2020-2022 cell-level costs projected by GM for its LG-supplied cells for the Chevy Bolt EV, and converted them to estimated pack-level costs per gross kWh. These estimated costs were shown to appear generally lower than the pack-level costs for BEV150 that were generated by the 2012 FRM analysis. Figure 2.121 extends this comparison to the pack-level costs for BEV200 projected by the Draft TAR analysis and this Proposed Determination analysis. As discussed in the Draft TAR, the Draft TAR projected costs were significantly lower than the costs projected in the 2012 FRM analysis. Further, the Proposed Determination figures are somewhat lower still. These new figures continue to appear consistent with and in many cases appear to remain conservative with respect to the trend established by the GM/LG pack-converted cost estimates.

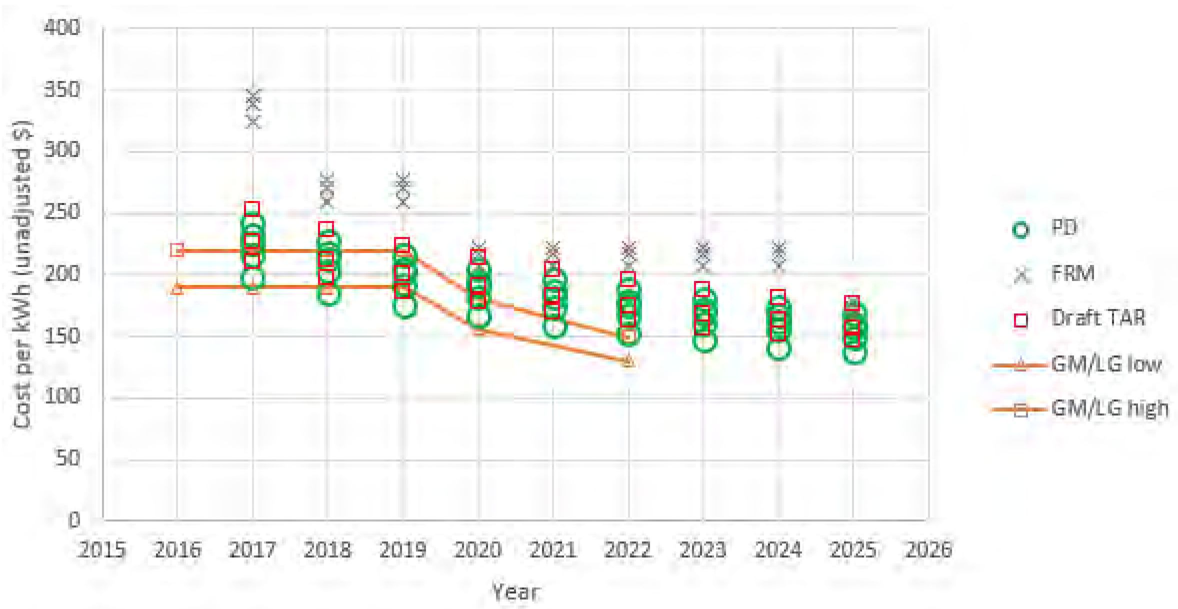


Figure 2.121 Comparison of Estimated Pack-Converted GM/LG Costs to BEV150/200 Projections of 2012 FRM, Draft TAR, and this Proposed Determination (PD)

As discussed in Draft TAR Section 5.2.4.4.9, comparisons of the GM/LG costs to those of the EPA analyses are subject to some uncertainty. As discussed in the Draft TAR, comparison on this basis to the 2012 FRM projections suggests that, rather than being overly optimistic, those projections may have been quite conservative with respect to trends in battery cost that have occurred since the FRM. This outcome suggests that EPA's battery costing methodology, with the updates and refinements discussed previously, is an appropriate basis on which to derive updated projections for this Proposed Determination analysis. As suggested throughout this analysis, it should be noted that battery costs have many drivers, and future cost projections derived by any methodology are subject to significant uncertainties.

2.3.4.3.7.7 Battery Pack Costs Used in OMEGA

Table 2.123 Linear Regressions of Strong Hybrid Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2017 (2015$)

Curb Weight Class	Strong HEV
1	-$187x+$1,001
2	-$212x+$1,046
3	-$239x+$1,068
4	-$279x+$1,122
5	-$344x+$1,183
6	-$347x+$1,196

Note: "x" in the equations represents the net weight reduction as a percentage.

Table 2.124 Linear Regressions of Battery Electric Battery System Direct Manufacturing Costs vs Net Mass Reduction Applicable in MY2025 (2015$)

Curb Weight Class	PHEV20	PHEV40	BEV75	BEV100	BEV200
1	-$441x+$2,448	-$403x+$3,223	-$761x+$3,820	-$1,098x+$4,295	-$1,711x+$5,931
2	-$1,152x+$2,591	-$499x+$3,468	-$1,136x+$3,987	-$1,564x+$4,523	-$2,244x+$6,253
3	-$504x+$2,641	-$565x+$3,614	-$1,313x+$4,096	-$1,951x+$4,691	-$2,606x+$6,459
4	-$535x+$2,790	$469x+$3,953	-$984x+$4,327	-$2,925x+$5,041	-$3,331x+$6,843
5	-$864x+$3,024	-$6,478x+$4,887	-$1,942x+$4,888	-$5,715x+$6,012	-$6,444x+$7,855
6	n/a	n/a	n/a	n/a	n/a

Note: "x" in the equations represents the net weight reduction as a percentage.

Table 2.125 Costs for MHEV48V Battery (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
All	DMC	$314	31	$314	$284	$265	$251	$240	$231	$223	$217	$211
All	IC	High1	2024	$177	$175	$174	$173	$172	$171	$171	$170	$105
All	TC			$490	$459	$438	$423	$412	$402	$394	$387	$316

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.126 Costs for Strong Hybrid Batteries (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	6	DMC	$990	31	$990	$896	$835	$791	$756	$728	$705	$685	$667
1	15	11	DMC	$980	31	$980	$888	$827	$783	$749	$721	$698	$678	$661
1	20	16	DMC	$971	31	$971	$879	$819	$776	$742	$714	$691	$672	$655
2	10	6	DMC	$1,033	31	$1,033	$936	$872	$826	$790	$760	$736	$715	$697
2	15	11	DMC	$1,023	31	$1,023	$926	$863	$817	$781	$753	$728	$708	$690
2	20	16	DMC	$1,012	31	$1,012	$917	$854	$809	$773	$745	$721	$700	$682
3	10	5	DMC	$1,056	31	$1,056	$957	$891	$844	$807	$777	$752	$731	$712
3	15	10	DMC	$1,044	31	$1,044	$946	$881	$834	$798	$768	$744	$723	$704
3	20	15	DMC	$1,032	31	$1,032	$935	$871	$825	$789	$760	$735	$714	$696
4	10	6	DMC	$1,105	31	$1,105	$1,001	$933	$883	$844	$813	$787	$765	$745
4	15	11	DMC	$1,091	31	$1,091	$988	$921	$872	$834	$803	$777	$755	$736
4	20	16	DMC	$1,077	31	$1,077	$976	$909	$861	$823	$793	$767	$745	$726
5	10	6	DMC	$1,162	31	$1,162	$1,052	$981	$928	$888	$855	$827	$804	$783
5	15	11	DMC	$1,145	31	$1,145	$1,037	$966	$915	$875	$842	$815	$792	$772
5	20	16	DMC	$1,128	31	$1,128	$1,021	$952	$901	$862	$830	$803	$780	$760
6	10	6	DMC	$1,175	31	$1,175	$1,064	$992	$939	$898	$865	$837	$813	$792
6	15	11	DMC	$1,158	31	$1,158	$1,049	$977	$925	$885	$852	$825	$801	$781

6	20	16	DMC	$1,141	31	$1,141	$1,033	$963	$911	$872	$839	$812	$789	$769
1	10	6	IC	High1	2024	$558	$552	$548	$545	$543	$541	$539	$538	$332
1	15	11	IC	High1	2024	$553	$547	$543	$540	$538	$536	$534	$533	$328
1	20	16	IC	High1	2024	$547	$541	$538	$535	$532	$531	$529	$528	$325
2	10	6	IC	High1	2024	$582	$576	$572	$569	$567	$565	$563	$562	$346
2	15	11	IC	High1	2024	$576	$570	$566	$563	$561	$559	$557	$556	$343
2	20	16	IC	High1	2024	$571	$564	$560	$557	$555	$553	$552	$550	$339
3	10	5	IC	High1	2024	$595	$589	$585	$582	$579	$577	$576	$574	$354
3	15	10	IC	High1	2024	$589	$582	$578	$575	$573	$571	$569	$568	$350
3	20	15	IC	High1	2024	$582	$576	$571	$568	$566	$564	$563	$561	$346
4	10	6	IC	High1	2024	$623	$616	$612	$609	$606	$604	$602	$601	$370
4	15	11	IC	High1	2024	$615	$608	$604	$601	$598	$596	$595	$593	$366
4	20	16	IC	High1	2024	$607	$601	$596	$593	$591	$589	$587	$586	$361
5	10	6	IC	High1	2024	$655	$648	$643	$640	$637	$635	$633	$632	$389
5	15	11	IC	High1	2024	$645	$638	$634	$630	$628	$626	$624	$622	$384
5	20	16	IC	High1	2024	$636	$629	$624	$621	$618	$616	$615	$613	$378
6	10	6	IC	High1	2024	$662	$655	$651	$647	$645	$642	$641	$639	$394
6	15	11	IC	High1	2024	$653	$646	$641	$638	$635	$633	$631	$630	$388
6	20	16	IC	High1	2024	$643	$636	$631	$628	$626	$623	$622	$620	$382
1	10	6	TC			$1,548	$1,448	$1,383	$1,336	$1,299	$1,269	$1,244	$1,223	$999
1	15	11	TC			$1,533	$1,434	$1,370	$1,323	$1,287	$1,257	$1,232	$1,211	$989
1	20	16	TC			$1,518	$1,421	$1,357	$1,311	$1,274	$1,245	$1,221	$1,200	$980
2	10	6	TC			$1,616	$1,512	$1,444	$1,395	$1,356	$1,325	$1,299	$1,277	$1,043
2	15	11	TC			$1,599	$1,496	$1,429	$1,380	$1,342	$1,312	$1,286	$1,264	$1,032
2	20	16	TC			$1,583	$1,481	$1,414	$1,366	$1,328	$1,298	$1,272	$1,251	$1,022
3	10	5	TC			$1,652	$1,545	$1,476	$1,426	$1,386	$1,355	$1,328	$1,305	$1,066
3	15	10	TC			$1,633	$1,528	$1,459	$1,409	$1,371	$1,339	$1,313	$1,290	$1,054
3	20	15	TC			$1,614	$1,510	$1,443	$1,393	$1,355	$1,324	$1,298	$1,276	$1,042
4	10	6	TC			$1,728	$1,617	$1,544	$1,492	$1,451	$1,417	$1,389	$1,366	$1,115
4	15	11	TC			$1,706	$1,597	$1,525	$1,473	$1,432	$1,399	$1,372	$1,348	$1,101
4	20	16	TC			$1,685	$1,576	$1,506	$1,454	$1,414	$1,382	$1,354	$1,331	$1,087
5	10	6	TC			$1,817	$1,700	$1,624	$1,568	$1,525	$1,490	$1,461	$1,436	$1,173
5	15	11	TC			$1,790	$1,675	$1,600	$1,545	$1,502	$1,468	$1,439	$1,414	$1,155
5	20	16	TC			$1,763	$1,650	$1,576	$1,522	$1,480	$1,446	$1,417	$1,393	$1,138
6	10	6	TC			$1,838	$1,720	$1,642	$1,586	$1,543	$1,507	$1,478	$1,452	$1,186
6	15	11	TC			$1,811	$1,694	$1,618	$1,563	$1,520	$1,485	$1,456	$1,431	$1,169
6	20	16	TC			$1,784	$1,669	$1,594	$1,539	$1,497	$1,463	$1,434	$1,409	$1,151

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.127 Costs for 20 Mile Plug-in Hybrid Batteries (dollar values in 2015$)

Curb Weight Class	WRtech	WRnet	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	15	6	DMC	$2,422	26	$3,906	$3,666	$3,466	$3,296	$3,150	$3,022	$2,908	$2,807	$2,716
1	20	11	DMC	$2,400	26	$3,871	$3,632	$3,434	$3,266	$3,121	$2,994	$2,882	$2,782	$2,691
2	15	6	DMC	$2,522	26	$4,068	$3,817	$3,609	$3,433	$3,280	$3,147	$3,029	$2,923	$2,828
2	20	11	DMC	$2,464	26	$3,975	$3,730	$3,527	$3,354	$3,205	$3,075	$2,960	$2,857	$2,764
3	15	6	DMC	$2,611	26	$4,211	$3,952	$3,736	$3,553	$3,396	$3,258	$3,135	$3,026	$2,928
3	20	11	DMC	$2,586	26	$4,171	$3,914	$3,700	$3,519	$3,363	$3,226	$3,105	$2,997	$2,900
4	15	6	DMC	$2,758	26	$4,449	$4,175	$3,947	$3,754	$3,587	$3,441	$3,312	$3,197	$3,093
4	20	11	DMC	$2,731	26	$4,405	$4,134	$3,909	$3,717	$3,552	$3,408	$3,280	$3,166	$3,063
5	15	6	DMC	$2,972	26	$4,793	$4,498	$4,253	$4,045	$3,865	$3,708	$3,569	$3,445	$3,333
5	20	11	DMC	$2,929	26	$4,724	$4,433	$4,191	$3,986	$3,809	$3,654	$3,517	$3,395	$3,284
1	15	6	IC	High2	2024	$1,974	$1,956	$1,942	$1,929	$1,918	$1,909	$1,901	$1,893	$1,217
1	20	11	IC	High2	2024	$1,956	$1,939	$1,924	$1,912	$1,901	$1,892	$1,883	$1,876	$1,206
2	15	6	IC	High2	2024	$2,056	$2,037	$2,022	$2,009	$1,998	$1,988	$1,979	$1,972	$1,267
2	20	11	IC	High2	2024	$2,009	$1,991	$1,976	$1,963	$1,952	$1,943	$1,934	$1,927	$1,239
3	15	6	IC	High2	2024	$2,128	$2,109	$2,093	$2,080	$2,068	$2,058	$2,049	$2,041	$1,312
3	20	11	IC	High2	2024	$2,108	$2,089	$2,073	$2,060	$2,048	$2,038	$2,029	$2,021	$1,299

4	15	6	IC	High2	2024	$2,248	$2,228	$2,211	$2,197	$2,185	$2,174	$2,165	$2,156	$1,386
4	20	11	IC	High2	2024	$2,226	$2,206	$2,190	$2,176	$2,164	$2,153	$2,144	$2,135	$1,373
5	15	6	IC	High2	2024	$2,422	$2,401	$2,383	$2,367	$2,354	$2,343	$2,332	$2,323	$1,493
5	20	11	IC	High2	2024	$2,387	$2,366	$2,348	$2,333	$2,320	$2,309	$2,298	$2,289	$1,472
1	15	6	TC			$5,880	$5,622	$5,407	$5,225	$5,068	$4,931	$4,809	$4,700	$3,933
1	20	11	TC			$5,827	$5,571	$5,358	$5,178	$5,022	$4,886	$4,765	$4,658	$3,897
2	15	6	TC			$6,124	$5,855	$5,631	$5,442	$5,278	$5,135	$5,008	$4,895	$4,096
2	20	11	TC			$5,984	$5,721	$5,503	$5,317	$5,158	$5,018	$4,894	$4,783	$4,002
3	15	6	TC			$6,339	$6,061	$5,830	$5,633	$5,464	$5,316	$5,185	$5,067	$4,240
3	20	11	TC			$6,278	$6,002	$5,773	$5,579	$5,411	$5,264	$5,134	$5,018	$4,199
4	15	6	TC			$6,697	$6,403	$6,158	$5,951	$5,772	$5,615	$5,477	$5,353	$4,479
4	20	11	TC			$6,632	$6,340	$6,098	$5,893	$5,716	$5,561	$5,424	$5,301	$4,436
5	15	6	TC			$7,216	$6,899	$6,635	$6,412	$6,219	$6,050	$5,901	$5,768	$4,826
5	20	11	TC			$7,111	$6,799	$6,539	$6,319	$6,129	$5,963	$5,815	$5,684	$4,756

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.128 Costs for 40 Mile Plug-in Hybrid Batteries (dollar values in 2015$)

Curb Weight Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	7	DMC	$3,195	26	$5,153	$4,836	$4,572	$4,348	$4,155	$3,986	$3,837	$3,703	$3,583
2	20	6	DMC	$3,438	26	$5,545	$5,203	$4,920	$4,679	$4,471	$4,289	$4,128	$3,985	$3,855
3	20	5	DMC	$3,585	26	$5,783	$5,427	$5,131	$4,880	$4,663	$4,474	$4,306	$4,156	$4,021
4	20	5	DMC	$3,976	26	$6,413	$6,018	$5,690	$5,412	$5,171	$4,961	$4,775	$4,609	$4,459
5	20	7	DMC	$4,433	26	$7,151	$6,710	$6,344	$6,034	$5,766	$5,532	$5,324	$5,139	$4,972
1	20	7	IC	High2	2024	$2,604	$2,581	$2,561	$2,545	$2,531	$2,518	$2,507	$2,497	$1,606
2	20	6	IC	High2	2024	$2,802	$2,777	$2,756	$2,739	$2,723	$2,710	$2,698	$2,687	$1,728
3	20	5	IC	High2	2024	$2,923	$2,896	$2,875	$2,856	$2,840	$2,826	$2,814	$2,803	$1,802
4	20	5	IC	High2	2024	$3,241	$3,212	$3,188	$3,167	$3,150	$3,134	$3,121	$3,108	$1,998
5	20	7	IC	High2	2024	$3,614	$3,582	$3,555	$3,532	$3,512	$3,495	$3,479	$3,466	$2,228
1	20	7	TC			$7,757	$7,416	$7,133	$6,893	$6,686	$6,504	$6,344	$6,201	$5,188
2	20	6	TC			$8,347	$7,980	$7,676	$7,417	$7,194	$6,999	$6,826	$6,672	$5,583
3	20	5	TC			$8,706	$8,323	$8,006	$7,736	$7,503	$7,300	$7,120	$6,959	$5,823
4	20	5	TC			$9,654	$9,230	$8,878	$8,579	$8,321	$8,095	$7,895	$7,717	$6,457
5	20	7	TC			$10,765	$10,292	$9,899	$9,566	$9,278	$9,026	$8,804	$8,605	$7,200

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.129 Costs for 75 Mile BEV Batteries (dollar values in 2015$)

Curb Weight Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	DMC	$3,743	26	$6,038	$5,666	$5,357	$5,095	$4,869	$4,671	$4,496	$4,339	$4,198
1	15	15	DMC	$3,705	26	$5,977	$5,609	$5,303	$5,043	$4,819	$4,623	$4,450	$4,295	$4,156
1	20	20	DMC	$3,667	26	$5,915	$5,551	$5,248	$4,991	$4,770	$4,576	$4,404	$4,251	$4,113
2	10	10	DMC	$3,874	26	$6,248	$5,863	$5,543	$5,272	$5,038	$4,833	$4,652	$4,490	$4,344
2	15	15	DMC	$3,817	26	$6,156	$5,777	$5,462	$5,195	$4,964	$4,762	$4,584	$4,424	$4,280
2	20	20	DMC	$3,760	26	$6,064	$5,691	$5,381	$5,117	$4,890	$4,691	$4,515	$4,358	$4,217
3	10	10	DMC	$3,965	26	$6,395	$6,001	$5,674	$5,396	$5,157	$4,947	$4,762	$4,596	$4,447
3	15	15	DMC	$3,899	26	$6,289	$5,902	$5,580	$5,307	$5,071	$4,865	$4,683	$4,520	$4,373
3	20	20	DMC	$3,834	26	$6,183	$5,803	$5,486	$5,218	$4,986	$4,783	$4,604	$4,444	$4,299
4	10	10	DMC	$4,229	26	$6,821	$6,401	$6,052	$5,756	$5,500	$5,277	$5,079	$4,902	$4,743
4	15	15	DMC	$4,180	26	$6,742	$6,326	$5,981	$5,689	$5,436	$5,215	$5,020	$4,845	$4,688
4	20	20	DMC	$4,131	26	$6,662	$6,252	$5,911	$5,622	$5,372	$5,154	$4,960	$4,788	$4,632
5	10	10	DMC	$4,694	26	$7,571	$7,105	$6,717	$6,389	$6,105	$5,857	$5,637	$5,441	$5,264

5	15	15	DMC	$4,597	26	$7,414	$6,958	$6,578	$6,256	$5,979	$5,735	$5,520	$5,328	$5,155
5	20	20	DMC	$4,500	26	$7,258	$6,811	$6,439	$6,124	$5,852	$5,614	$5,404	$5,216	$5,046
1	10	10	IC	High2	2024	$3,052	$3,024	$3,001	$2,982	$2,965	$2,951	$2,938	$2,926	$1,881
1	15	15	IC	High2	2024	$3,021	$2,993	$2,971	$2,952	$2,935	$2,921	$2,908	$2,897	$1,862
1	20	20	IC	High2	2024	$2,990	$2,963	$2,940	$2,922	$2,905	$2,891	$2,878	$2,867	$1,843
2	10	10	IC	High2	2024	$3,158	$3,129	$3,106	$3,086	$3,068	$3,053	$3,040	$3,028	$1,947
2	15	15	IC	High2	2024	$3,111	$3,083	$3,060	$3,040	$3,023	$3,009	$2,995	$2,984	$1,918
2	20	20	IC	High2	2024	$3,065	$3,037	$3,015	$2,995	$2,978	$2,964	$2,951	$2,939	$1,890
3	10	10	IC	High2	2024	$3,232	$3,203	$3,179	$3,159	$3,141	$3,125	$3,112	$3,100	$1,993
3	15	15	IC	High2	2024	$3,179	$3,150	$3,126	$3,106	$3,089	$3,074	$3,060	$3,048	$1,960
3	20	20	IC	High2	2024	$3,125	$3,097	$3,074	$3,054	$3,037	$3,022	$3,009	$2,997	$1,927
4	10	10	IC	High2	2024	$3,447	$3,416	$3,391	$3,369	$3,350	$3,334	$3,319	$3,306	$2,125
4	15	15	IC	High2	2024	$3,407	$3,377	$3,351	$3,330	$3,311	$3,295	$3,280	$3,268	$2,101
4	20	20	IC	High2	2024	$3,367	$3,337	$3,312	$3,290	$3,272	$3,256	$3,242	$3,229	$2,076
5	10	10	IC	High2	2024	$3,826	$3,792	$3,763	$3,739	$3,718	$3,700	$3,684	$3,669	$2,359
5	15	15	IC	High2	2024	$3,747	$3,714	$3,686	$3,662	$3,641	$3,624	$3,608	$3,594	$2,310
5	20	20	IC	High2	2024	$3,668	$3,635	$3,608	$3,585	$3,564	$3,547	$3,531	$3,518	$2,261
1	10	10	TC			$9,090	$8,690	$8,359	$8,077	$7,834	$7,622	$7,434	$7,266	$6,080
1	15	15	TC			$8,997	$8,602	$8,274	$7,995	$7,755	$7,544	$7,358	$7,192	$6,018
1	20	20	TC			$8,905	$8,514	$8,189	$7,913	$7,675	$7,467	$7,283	$7,118	$5,956
2	10	10	TC			$9,405	$8,992	$8,649	$8,358	$8,106	$7,886	$7,692	$7,518	$6,291
2	15	15	TC			$9,267	$8,860	$8,522	$8,235	$7,987	$7,771	$7,579	$7,408	$6,198
2	20	20	TC			$9,129	$8,728	$8,395	$8,112	$7,868	$7,655	$7,466	$7,297	$6,106
3	10	10	TC			$9,627	$9,204	$8,853	$8,555	$8,298	$8,073	$7,873	$7,696	$6,439
3	15	15	TC			$9,468	$9,052	$8,707	$8,413	$8,160	$7,939	$7,743	$7,568	$6,333
3	20	20	TC			$9,309	$8,900	$8,560	$8,272	$8,023	$7,805	$7,613	$7,441	$6,226
4	10	10	TC			$10,268	$9,817	$9,443	$9,125	$8,850	$8,610	$8,398	$8,208	$6,868
4	15	15	TC			$10,149	$9,703	$9,333	$9,018	$8,747	$8,510	$8,300	$8,112	$6,788
4	20	20	TC			$10,029	$9,589	$9,223	$8,912	$8,644	$8,410	$8,202	$8,017	$6,708
5	10	10	TC			$11,397	$10,897	$10,481	$10,128	$9,823	$9,557	$9,321	$9,110	$7,623
5	15	15	TC			$11,161	$10,671	$10,264	$9,918	$9,620	$9,359	$9,128	$8,922	$7,465
5	20	20	TC			$10,926	$10,446	$10,047	$9,709	$9,417	$9,161	$8,935	$8,733	$7,308

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.130 Costs for 100 Mile BEV Batteries (dollar values in 2015$)

Curb Weight Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	DMC	$4,185	26	$6,750	$6,334	$5,989	$5,696	$5,443	$5,221	$5,026	$4,851	$4,693
1	15	15	DMC	$4,130	26	$6,661	$6,251	$5,910	$5,621	$5,371	$5,153	$4,960	$4,787	$4,632
1	20	20	DMC	$4,075	26	$6,573	$6,168	$5,832	$5,546	$5,300	$5,085	$4,894	$4,724	$4,570
2	10	10	DMC	$4,367	26	$7,044	$6,610	$6,249	$5,943	$5,680	$5,449	$5,244	$5,062	$4,897
2	15	15	DMC	$4,289	26	$6,917	$6,491	$6,137	$5,837	$5,578	$5,351	$5,150	$4,971	$4,810
2	20	20	DMC	$4,210	26	$6,791	$6,373	$6,025	$5,731	$5,476	$5,253	$5,056	$4,880	$4,722
3	10	9	DMC	$4,516	26	$7,284	$6,835	$6,463	$6,146	$5,873	$5,635	$5,423	$5,234	$5,065
3	15	14	DMC	$4,418	26	$7,127	$6,688	$6,323	$6,014	$5,746	$5,513	$5,306	$5,121	$4,955
3	20	19	DMC	$4,321	26	$6,969	$6,540	$6,183	$5,881	$5,620	$5,391	$5,189	$5,008	$4,846
4	10	10	DMC	$4,748	26	$7,659	$7,187	$6,795	$6,462	$6,176	$5,924	$5,702	$5,504	$5,325
4	15	15	DMC	$4,602	26	$7,423	$6,966	$6,586	$6,263	$5,985	$5,742	$5,527	$5,334	$5,161
4	20	20	DMC	$4,456	26	$7,187	$6,744	$6,376	$6,064	$5,795	$5,559	$5,351	$5,165	$4,997
5	10	10	DMC	$5,441	26	$8,776	$8,235	$7,786	$7,405	$7,076	$6,789	$6,534	$6,307	$6,102
5	15	15	DMC	$5,155	26	$8,315	$7,803	$7,377	$7,016	$6,705	$6,432	$6,191	$5,976	$5,782
5	20	20	DMC	$4,870	26	$7,854	$7,370	$6,969	$6,628	$6,333	$6,076	$5,848	$5,644	$5,461
1	10	10	IC	High2	2024	$3,411	$3,381	$3,355	$3,334	$3,315	$3,299	$3,284	$3,272	$2,103
1	15	15	IC	High2	2024	$3,367	$3,336	$3,311	$3,290	$3,272	$3,256	$3,241	$3,229	$2,075
1	20	20	IC	High2	2024	$3,322	$3,292	$3,267	$3,246	$3,228	$3,212	$3,198	$3,186	$2,048
2	10	10	IC	High2	2024	$3,560	$3,528	$3,501	$3,479	$3,459	$3,442	$3,427	$3,414	$2,195
2	15	15	IC	High2	2024	$3,496	$3,465	$3,439	$3,416	$3,397	$3,381	$3,366	$3,353	$2,155
2	20	20	IC	High2	2024	$3,432	$3,401	$3,376	$3,354	$3,335	$3,319	$3,305	$3,292	$2,116

3	10	9	IC	High2	2024	$3,681	$3,648	$3,621	$3,597	$3,577	$3,560	$3,544	$3,530	$2,269
3	15	14	IC	High2	2024	$3,602	$3,569	$3,543	$3,520	$3,500	$3,483	$3,468	$3,454	$2,220
3	20	19	IC	High2	2024	$3,522	$3,491	$3,464	$3,442	$3,423	$3,406	$3,391	$3,378	$2,171
4	10	10	IC	High2	2024	$3,871	$3,836	$3,807	$3,783	$3,761	$3,743	$3,727	$3,712	$2,386
4	15	15	IC	High2	2024	$3,751	$3,718	$3,690	$3,666	$3,646	$3,628	$3,612	$3,598	$2,313
4	20	20	IC	High2	2024	$3,632	$3,600	$3,572	$3,550	$3,530	$3,512	$3,497	$3,483	$2,239
5	10	10	IC	High2	2024	$4,435	$4,395	$4,362	$4,334	$4,310	$4,289	$4,270	$4,253	$2,734
5	15	15	IC	High2	2024	$4,202	$4,165	$4,133	$4,107	$4,084	$4,064	$4,046	$4,030	$2,591
5	20	20	IC	High2	2024	$3,969	$3,934	$3,904	$3,879	$3,857	$3,839	$3,822	$3,807	$2,447
1	10	10	TC			$10,161	$9,715	$9,344	$9,029	$8,758	$8,520	$8,310	$8,122	$6,796
1	15	15	TC			$10,028	$9,587	$9,222	$8,911	$8,643	$8,409	$8,201	$8,016	$6,707
1	20	20	TC			$9,895	$9,460	$9,099	$8,793	$8,528	$8,297	$8,092	$7,909	$6,618
2	10	10	TC			$10,603	$10,137	$9,751	$9,422	$9,139	$8,891	$8,672	$8,476	$7,092
2	15	15	TC			$10,413	$9,956	$9,576	$9,253	$8,975	$8,732	$8,516	$8,324	$6,965
2	20	20	TC			$10,224	$9,774	$9,401	$9,085	$8,811	$8,572	$8,361	$8,172	$6,838
3	10	9	TC			$10,965	$10,483	$10,083	$9,744	$9,451	$9,194	$8,967	$8,765	$7,334
3	15	14	TC			$10,728	$10,257	$9,865	$9,533	$9,247	$8,996	$8,774	$8,575	$7,176
3	20	19	TC			$10,491	$10,031	$9,648	$9,323	$9,042	$8,797	$8,580	$8,386	$7,017
4	10	10	TC			$11,529	$11,023	$10,602	$10,245	$9,937	$9,667	$9,429	$9,216	$7,711
4	15	15	TC			$11,174	$10,683	$10,275	$9,929	$9,631	$9,370	$9,138	$8,932	$7,474
4	20	20	TC			$10,819	$10,344	$9,949	$9,614	$9,325	$9,072	$8,848	$8,648	$7,236
5	10	10	TC			$13,211	$12,631	$12,149	$11,740	$11,387	$11,078	$10,804	$10,560	$8,836
5	15	15	TC			$12,518	$11,968	$11,511	$11,123	$10,789	$10,496	$10,237	$10,006	$8,372
5	20	20	TC			$11,824	$11,304	$10,873	$10,507	$10,191	$9,914	$9,670	$9,451	$7,908

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.131 Costs for 200 Mile BEV Batteries (dollar values in 2015$)

Curb Weight Class	WR tech	WR net	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	13	DMC	$5,709	26	$9,208	$8,641	$8,170	$7,770	$7,425	$7,123	$6,856	$6,617	$6,402
2	20	14	DMC	$5,939	26	$9,580	$8,989	$8,499	$8,083	$7,724	$7,410	$7,132	$6,884	$6,661
3	20	13	DMC	$6,120	26	$9,871	$9,263	$8,758	$8,329	$7,960	$7,636	$7,350	$7,094	$6,863
4	20	14	DMC	$6,377	26	$10,285	$9,652	$9,125	$8,679	$8,293	$7,956	$7,658	$7,391	$7,151
5	20	14	DMC	$6,953	26	$11,215	$10,524	$9,950	$9,463	$9,043	$8,675	$8,350	$8,059	$7,798
1	20	13	IC	High2	2024	$4,654	$4,612	$4,577	$4,548	$4,522	$4,500	$4,480	$4,463	$2,869
2	20	14	IC	High2	2024	$4,841	$4,798	$4,762	$4,731	$4,705	$4,682	$4,661	$4,643	$2,985
3	20	13	IC	High2	2024	$4,989	$4,944	$4,907	$4,875	$4,848	$4,824	$4,803	$4,784	$3,076
4	20	14	IC	High2	2024	$5,198	$5,151	$5,113	$5,080	$5,051	$5,027	$5,005	$4,985	$3,205
5	20	14	IC	High2	2024	$5,668	$5,617	$5,575	$5,539	$5,508	$5,481	$5,457	$5,435	$3,494
1	20	13	TC			$13,861	$13,253	$12,747	$12,317	$11,947	$11,623	$11,336	$11,080	$9,271
2	20	14	TC			$14,421	$13,787	$13,261	$12,815	$12,429	$12,092	$11,794	$11,527	$9,645
3	20	13	TC			$14,860	$14,207	$13,665	$13,205	$12,808	$12,460	$12,153	$11,878	$9,939
4	20	14	TC			$15,483	$14,803	$14,238	$13,759	$13,345	$12,983	$12,662	$12,376	$10,356
5	20	14	TC			$16,883	$16,141	$15,525	$15,002	$14,551	$14,156	$13,807	$13,495	$11,292

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.3.7.8 Electrified Vehicle Costs Used In OMEGA (Battery + Non-battery Items)

Costs presented in the tables that follow sum the battery, non-battery and, where applicable, the in-home charger related costs for mild, strong and plug-in hybrids and full battery electric vehicles.

Table 2.132 Full System Costs for 48V Mild Hybrids (2015$)

Curb Weight Class	WRtech	WRnet	Cost Type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	5	1.5	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814
2	5	2	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814
3	5	2.5	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814
4	5	2.5	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814
5	5	2.5	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814
6	5	3	TC	$1,073	$1,035	$965	$944	$927	$913	$900	$889	$814

Note: TC=total costs.

Table 2.133 Full System Costs for Strong Hybrids (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	6	TC	$4,225	$4,097	$3,615	$3,545	$3,486	$3,436	$3,392	$3,353	$3,112
1	15	11	TC	$4,189	$4,063	$3,585	$3,515	$3,457	$3,408	$3,364	$3,325	$3,087
1	20	16	TC	$4,154	$4,029	$3,554	$3,485	$3,428	$3,379	$3,336	$3,297	$3,061
2	10	6	TC	$4,512	$4,378	$3,859	$3,784	$3,723	$3,670	$3,623	$3,581	$3,329
2	15	11	TC	$4,468	$4,335	$3,821	$3,747	$3,686	$3,634	$3,588	$3,547	$3,297
2	20	16	TC	$4,424	$4,293	$3,783	$3,710	$3,650	$3,598	$3,552	$3,512	$3,265
3	10	5	TC	$4,628	$4,491	$3,957	$3,881	$3,818	$3,764	$3,716	$3,673	$3,416
3	15	10	TC	$4,579	$4,443	$3,915	$3,840	$3,777	$3,724	$3,677	$3,634	$3,380
3	20	15	TC	$4,530	$4,396	$3,873	$3,799	$3,737	$3,684	$3,637	$3,595	$3,343
4	10	6	TC	$4,817	$4,674	$4,120	$4,040	$3,975	$3,918	$3,868	$3,824	$3,554
4	15	11	TC	$4,757	$4,615	$4,068	$3,989	$3,924	$3,869	$3,819	$3,776	$3,509
4	20	16	TC	$4,696	$4,556	$4,016	$3,939	$3,874	$3,819	$3,771	$3,727	$3,465
5	10	6	TC	$5,222	$5,070	$4,463	$4,378	$4,307	$4,246	$4,193	$4,145	$3,861
5	15	11	TC	$5,148	$4,998	$4,399	$4,315	$4,246	$4,186	$4,134	$4,086	$3,806
5	20	16	TC	$5,074	$4,926	$4,336	$4,253	$4,185	$4,126	$4,074	$4,028	$3,752
6	10	6	TC	$5,256	$5,102	$4,492	$4,406	$4,335	$4,274	$4,220	$4,172	$3,884
6	15	11	TC	$5,179	$5,027	$4,426	$4,342	$4,271	$4,211	$4,158	$4,111	$3,828
6	20	16	TC	$5,102	$4,952	$4,360	$4,277	$4,208	$4,149	$4,096	$4,050	$3,771

Note: TC=total costs.

Table 2.134 Full System Costs for 20 Mile Plug-in Hybrids, Including Charger & Charger Labor (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	15	6	TC	$10,259	$9,964	$9,248	$9,036	$8,851	$8,688	$8,542	$8,410	$7,614
1	20	11	TC	$10,209	$9,916	$9,202	$8,991	$8,808	$8,646	$8,501	$8,370	$7,581
2	15	6	TC	$10,827	$10,518	$9,743	$9,520	$9,326	$9,155	$9,001	$8,863	$8,033
2	20	11	TC	$10,692	$10,389	$9,618	$9,400	$9,209	$9,041	$8,891	$8,755	$7,943
3	15	6	TC	$11,164	$10,844	$10,042	$9,811	$9,611	$9,433	$9,275	$9,132	$8,273
3	20	11	TC	$11,107	$10,790	$9,989	$9,761	$9,562	$9,386	$9,229	$9,087	$8,236
4	15	6	TC	$11,768	$11,430	$10,576	$10,333	$10,120	$9,933	$9,765	$9,614	$8,707
4	20	11	TC	$11,709	$11,374	$10,522	$10,280	$10,070	$9,883	$9,717	$9,567	$8,668
5	15	6	TC	$12,750	$12,384	$11,439	$11,176	$10,946	$10,743	$10,561	$10,397	$9,419
5	20	11	TC	$12,653	$12,292	$11,349	$11,089	$10,862	$10,661	$10,481	$10,319	$9,355

Note: TC=total costs.

Table 2.135 Full System Costs for 40 Mile Plug-in Hybrids, Including Charger & Charger Labor (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	7	TC	$13,163	$12,763	$11,855	$11,568	$11,318	$11,098	$10,901	$10,724	$9,641
2	20	6	TC	$14,370	$13,936	$12,917	$12,605	$12,333	$12,092	$11,878	$11,685	$10,515
3	20	5	TC	$14,990	$14,535	$13,467	$13,141	$12,856	$12,605	$12,381	$12,179	$10,955
4	20	5	TC	$16,479	$15,978	$14,791	$14,430	$14,116	$13,839	$13,591	$13,368	$12,017
5	20	7	TC	$18,327	$17,769	$16,427	$16,026	$15,676	$15,367	$15,091	$14,842	$13,342

Note: TC=total costs.

Table 2.136 Full System Costs for 75 Mile BEVs, Including Charger & Charger Labor (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	TC	$10,660	$10,240	$9,892	$9,596	$9,340	$9,117	$8,920	$8,744	$7,464
1	15	15	TC	$10,569	$10,153	$9,808	$9,514	$9,262	$9,041	$8,845	$8,670	$7,404
1	20	20	TC	$10,478	$10,066	$9,724	$9,433	$9,183	$8,964	$8,770	$8,597	$7,344
2	10	10	TC	$11,520	$11,076	$10,708	$10,395	$10,124	$9,887	$9,678	$9,490	$8,121
2	15	15	TC	$11,395	$10,957	$10,594	$10,285	$10,018	$9,784	$9,577	$9,392	$8,039
2	20	20	TC	$11,269	$10,838	$10,479	$10,174	$9,911	$9,680	$9,476	$9,294	$7,957
3	10	10	TC	$11,128	$10,690	$10,328	$10,021	$9,756	$9,525	$9,320	$9,138	$7,700
3	15	15	TC	$10,970	$10,540	$10,183	$9,880	$9,620	$9,392	$9,191	$9,011	$7,596
3	20	20	TC	$10,812	$10,389	$10,037	$9,740	$9,483	$9,259	$9,061	$8,885	$7,493
4	10	10	TC	$11,929	$11,454	$11,059	$10,724	$10,434	$10,181	$9,957	$9,757	$8,349
4	15	15	TC	$11,828	$11,358	$10,967	$10,635	$10,349	$10,099	$9,877	$9,679	$8,284
4	20	20	TC	$11,727	$11,262	$10,875	$10,547	$10,264	$10,016	$9,797	$9,601	$8,218
5	10	10	TC	$14,070	$13,532	$13,084	$12,704	$12,375	$12,086	$11,831	$11,602	$9,884
5	15	15	TC	$13,857	$13,329	$12,890	$12,516	$12,193	$11,910	$11,659	$11,435	$9,743
5	20	20	TC	$13,643	$13,126	$12,695	$12,328	$12,012	$11,734	$11,488	$11,268	$9,603

Note: TC=total costs.

Table 2.137 Full System Costs for 100 Mile BEVs, Including Charger & Charger Labor (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	10	10	TC	$11,732	$11,265	$10,877	$10,548	$10,264	$10,016	$9,796	$9,600	$8,180
1	15	15	TC	$11,600	$11,139	$10,755	$10,430	$10,150	$9,905	$9,688	$9,494	$8,093
1	20	20	TC	$11,468	$11,012	$10,634	$10,313	$10,036	$9,794	$9,580	$9,388	$8,006
2	10	10	TC	$12,718	$12,222	$11,809	$11,459	$11,157	$10,892	$10,657	$10,448	$8,923
2	15	15	TC	$12,540	$12,053	$11,647	$11,303	$11,005	$10,745	$10,514	$10,308	$8,805
2	20	20	TC	$12,363	$11,884	$11,485	$11,146	$10,854	$10,598	$10,371	$10,168	$8,688
3	10	9	TC	$12,465	$11,969	$11,558	$11,209	$10,909	$10,646	$10,414	$10,207	$8,594
3	15	14	TC	$12,230	$11,744	$11,341	$11,000	$10,706	$10,448	$10,221	$10,018	$8,439
3	20	19	TC	$11,995	$11,519	$11,125	$10,791	$10,503	$10,251	$10,028	$9,830	$8,283
4	10	10	TC	$13,190	$12,659	$12,218	$11,844	$11,521	$11,238	$10,988	$10,765	$9,192
4	15	15	TC	$12,853	$12,338	$11,910	$11,546	$11,233	$10,958	$10,715	$10,498	$8,969
4	20	20	TC	$12,516	$12,016	$11,601	$11,248	$10,944	$10,678	$10,442	$10,232	$8,746
5	10	10	TC	$15,883	$15,266	$14,752	$14,315	$13,938	$13,607	$13,314	$13,052	$11,097
5	15	15	TC	$15,212	$14,625	$14,136	$13,721	$13,361	$13,047	$12,768	$12,518	$10,650
5	20	20	TC	$14,541	$13,984	$13,520	$13,126	$12,785	$12,486	$12,221	$11,985	$10,203

Note: TC=total costs.

Table 2.138 Full System Costs for 200 Mile BEVs, Including Charger & Charger Labor (2015$)

Curb Weight Class	WRtech	WRnet	Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	20	13	TC	$15,433	$14,803	$14,280	$13,837	$13,454	$13,119	$12,823	$12,558	$10,657
2	20	14	TC	$16,546	$15,882	$15,331	$14,862	$14,458	$14,103	$13,790	$13,509	$11,485
3	20	13	TC	$16,361	$15,694	$15,141	$14,671	$14,267	$13,913	$13,600	$13,321	$11,202
4	20	14	TC	$17,158	$16,453	$15,868	$15,371	$14,943	$14,567	$14,236	$13,939	$11,848
5	20	14	TC	$19,636	$18,856	$18,207	$17,656	$17,180	$16,762	$16,393	$16,062	$13,615

Note: TC=total costs.

2.3.4.4 Aerodynamics: Data and Assumptions for this Assessment

For this Proposed Determination, as in the Draft TAR, EPA has considered two levels of aerodynamic improvements: Aero1 and Aero2. The first level, Aero1, represents a 10 percent reduction in drag from a baseline MY2008-level vehicle. The second level, Aero2, represents a 20 percent reduction from the same baseline (nominally, 10 percentage points incremental to Aero1).

In Chapter 2.2.5 of this TSD, EPA further considered the feasibility of aerodynamic improvements of this general degree, outlining examples that show that manufacturers are gaining aerodynamic benefits by implementing several varieties of passive and active aerodynamic technologies in current vehicles, while a range of opportunities remain to further apply these and other passive and active technologies in a more optimized fashion as vehicles enter redesign cycles in the future. That chapter also noted that for this Proposed Determination analysis, EPA has provided for a better representation of the existence of applied aerodynamic technology in the baseline fleet (as further described in this section).

The findings of the vehicle technology review and additional technology benefits evaluated in the Joint Aerodynamics Assessment Program (described in Chapter 2.2.5) also lend support to the feasibility of 10 percent and 20 percent improvements relative a MY2008-level baseline. As noted in the Draft TAR, the NAS report also generally supported the assumptions for 10 percent and 20 percent aerodynamic improvement as being applicable to the 2020 to 2025 time frame, relative a MY2008-level baseline.

During the Draft TAR comment period, EPA received confidential comments from a stakeholder that included piece-cost estimates for underbody covers that were higher than EPA's Aero1 DMCs. The extent of the underbody covers for this particular application was greater than the engine compartment underbody covers assumed within EPA's cost estimate for Aero1, and is more consistent with the type of treatment that EPA assumes will be required to achieve Aero2 levels. Furthermore, to the extent that the piece-cost estimates provided by the commenter are influenced by the additional function of this particular application of protecting vulnerable underbody components, the resulting costs would be expected to be higher than an underbody cover that has the sole purpose of drag reduction. For the Proposed Determination analysis, EPA is continuing to use the Draft TAR cost and effectiveness assumptions for passive and active aerodynamic technologies, updated to 2015 dollars.

Several stakeholders submitted comments on EPA's treatment of aerodynamic improvements in the baseline fleet. In particular, commenters noted that EPA's assumption that a 20 percent reduction in aerodynamic drag is equally feasible for all vehicles in the baseline fleet does not account for the drag reduction that some vehicles have already adopted. The Alliance and individual OEMs including Ford, Mercedes-Benz, Toyota, and FCA, all recommended that EPA adjust the aero levels in the baseline fleet to reflect appropriate drag reduction achieved by each vehicle.

EPA agrees that aerodynamic drag reductions have been achieved in some MY2015 vehicles relative to the levels of drag in MY2008-2010 designs that were used as the null technology point of reference for the FRM and Draft TAR. Furthermore, EPA agrees with the commenters that it is appropriate to account for aerodynamic drag reductions already present in the baseline fleet in order to avoid overestimating the amount of additional improvement that can be achieved at a given cost. Therefore, for this Proposed Determination, EPA has estimated the levels of aerodynamic drag reduction already present in MY2015, and assigned one of three aerodynamic levels to each vehicle in the baseline fleet. The process for determining the levels of Aero0, Aero1, and Aero2 is described below.

Using coast down coefficient values reported to EPA for vehicle certification, a value for the drag area, C_dA, was calculated for each vehicle in the MY2015 baseline fleet according to Equation 16.

Equation 16. Aerodynamic Drag Area Calculation from Coast Down Coefficients

$$C_dA = (B + 2Cv)/(pv)$$

In which:
B: Road load Coefficient (lbf/mph)
C: Road load Coefficient (lbf/mph2)
p: Air Density
v: Vehicle Speed at Aero Evaluation (68.2 mph (110 kmph))

Differences in frontal area and overall shape will directly influence a vehicle's calculated drag area. Because these characteristics tend to vary significantly across market segments, EPA categorized the MY2015 fleet using the size classifications defined in 40 CFR §600.315-08. These classes are defined by vehicle interior volume and side profile shape, such that vehicles with similar frontal areas and overall shape tend to be grouped together. For example, despite having similar side profile shapes, small pickups are distinguished from standard pickups to account for differences in frontal area. Within each of these vehicle size classes, the distribution of calculated drag areas across the MY2015 fleet was then investigated in order to determine appropriate cutoff values of C_dA that would delineate between different levels of aerodynamic drag. Table 2.140 shows the 50th percentile values of CdA defining the cutoff between Aero0 and Aero1 levels, and the 10th percentile values of C_dA defining the cutoff between Aero1 and Aero2 levels.

Table 2.139 MY2015 Aerodynamic Drag Area Statistics and Cutoff Values by Size Class

EPA Size Class	Production Volume	CdA (ft2) Statistics*		CdA (ft2) Cutoff Values	
		Average	Standard Deviation	Aero0 to Aero1 50th percentile	Aero1 to Aero2 10th percentile
Two Seaters	78,117	7.50	1.10	7.01	6.29
Subcompact Cars	418,583	7.90	0.58	8.19	7.10
Minicompact Cars	56,307	7.57	0.25	7.51	7.30
Compact Cars	1,760,020	7.48	0.69	7.57	6.69
Midsize Cars	3,363,603	7.67	0.58	7.68	6.83
Large Cars	735,631	7.74	1.06	7.72	6.52
Small Station Wagons	371,522	9.01	1.04	9.77	7.41
Midsize Station Wagons	110,423	9.27	0.55	9.55	8.25
Small SUV 2WD	1,589,325	10.22	0.87	10.28	9.12
Small SUV 4WD	2,620,222	10.80	1.58	10.42	9.23
Special Purpose Vehicle, minivan 2WD	519,773	10.56	0.88	10.48	9.32
Standard SUV 2WD	260,287	11.96	1.58	12.16	9.91
Standard SUV 4WD	1,253,047	12.22	1.18	11.86	11.11
Small Pick-up Trucks 2WD	162,243	12.24	1.14	11.93	11.18
Small Pick-up Trucks 4WD	178,391	13.08	0.87	13.77	11.92
Standard Pick-up Trucks 2WD	248,320	14.25	0.74	14.35	13.72

Standard Pick-up Trucks 4WD	1,016,923	14.26	1.78	15.13	12.14

*Note: Aerodynamic drag area statistics are weighted by MY2015 actual production volumes. Special Purpose Vehicle and Van classes with production under 100,000 not shown for clarity.

The 50th and 10th percentile cutoff values shown above were chosen to establish the aerodynamic drag reductions of 10 percent for Aero1 and 20 percent Aero2, relative to Aero 0. As shown in Table 2.140, across all classes the production weighted average reduction in drag area between the midpoints of the C_dA ranges is 10 percent moving from Aero0 to Aero1, and 22 percent moving from Aero0 to Aero2.

Table 2.140 Aerodynamic Drag Reduction Between Aero levels 0,1, and 2 by Size Class

	CdA (ft2)			**Drag Reduction**	
EPA Size Class	**Aero0 midpoint**	**Aero1 midpoint**	**Aero2 midpoint**	**Aero0 to Aero1**	**Aero0 to Aero2**
Two Seaters	7.71	6.65	5.98	14%	22%
Subcompact Cars	8.20	7.65	6.46	7%	21%
Minicompact Cars	7.72	7.40	7.26	4%	6%
Compact Cars	7.79	7.13	6.05	8%	22%
Midsize Cars	7.85	7.25	6.21	8%	21%
Large Cars	8.27	7.12	6.35	14%	23%
Small Station Wagons	9.94	8.59	7.28	14%	27%
Midsize Station Wagons	9.72	8.90	7.98	8%	18%
Small SUV 2WD	10.91	9.70	8.17	11%	25%
Small SUV 4WD	11.36	9.82	8.68	13%	24%
Special Purpose Vehicle, minivan 2WD	10.96	9.90	9.33	10%	15%
Standard SUV 2WD	12.93	11.03	9.89	15%	24%
Standard SUV 4WD	12.64	11.48	10.14	9%	20%
Small Pick-up Trucks 2WD	12.90	11.56	11.06	10%	14%
Small Pick-up Trucks 4WD	13.69	12.85	11.90	6%	13%
Standard Pick-up Trucks 2WD	14.84	14.04	12.89	5%	13%
Standard Pick-up Trucks 4WD	15.58	13.64	12.14	12%	22%
All size classes (production weighted)	**-**	**-**	**-**	**10%**	**22%**

In response to the comments received on the Draft TAR regarding an appropriate approach for considering aerodynamics in the baseline fleet, EPA has applied some level of aerodynamic drag reduction to a significant portion of the MY2015 baseline fleet for this Proposed Determination using the approach described above. Specifically, one half of the fleet volume in MY2015 has Aero1 or Aero2 levels. The remaining vehicles have the potential for additional improvement. As evidenced by the distribution of drag area values over the various size classes, the 20 percent improvement from Aero0 to Aero2 is an appropriate assumption for this remaining one half of MY2015 fleet volume.

The efficiencies are different per lumped parameter model classifications, as shown in Table , and costs are assigned per those in the Draft TAR.

Table 2.141 CO_2 Efficiency Improvement per 10% Aero Improvement per Vehicle Classification

ALPHA Class	CO2 Efficiency Improvement per 10% Aero Improvement
LPW_LRL	2.4%
MPW_LRL	2.2%
HPW	1.8%
LPW_HRL	2.6%
MPW_HRL	2.2%
Truck	2.5%

Costs associated with aero treatments and technologies are equivalent to those used in the Draft TAR except for updates to 2015 dollars. The aero costs are shown below in Table 2.142.

Table 2.142 Costs for Aero Technologies (dollar values in 2015$)

Tech	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
Passive aero	DMC	$44	24	$42	$41	$41	$40	$39	$39	$38	$38	$37
Passive aero	IC	Low2	2018	$11	$11	$8	$8	$8	$8	$8	$8	$8
Passive aero	TC			$53	$52	$49	$48	$48	$47	$47	$46	$46
Active aero	DMC	$132	24	$126	$124	$122	$120	$118	$116	$115	$113	$112
Active aero	IC	Med2	2024	$51	$51	$51	$51	$51	$50	$50	$50	$38
Active aero	TC			$177	$175	$173	$170	$168	$167	$165	$163	$149
Passive+Active	TC			$230	$227	$222	$219	$216	$214	$212	$209	$195

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

One comment was received, from FCA, which stated that the costs for aerodynamic technology is too low. EPA believes that a 10 percent improved C_dA can be achieved through the application of some commonly used aerodynamic treatments. For example, bumper modifications, wheel deflectors, rear spoiler and underbody cover are enough to provide a 10 percent reduction in aerodynamic drag for some vehicles. This is represented by a cost estimate of $44.00 and Low2 indirect costs as shown in Table 2.41. EPA believes that a 20 percent improvement in C_dA has been shown to be achieved by ancillary aerodynamic technologies, such as grille shutters and changes to vehicle exterior design. This is represented by a cost estimate of $132 and Medium2 Indirect Cost.

2.3.4.5 Tires: Data and Assumptions for this Assessment

In the Draft TAR, EPA considered two levels of low rolling resistance technology: LRRT1 and LRRT2. The first level, LRRT1, was defined as a 10 percent reduction in rolling resistance from a base (null technology) tire, made possible by methods such as increased tire diameter and sidewall stiffness and reduced aspect ratios (coupled with reduction in rotational inertia). The second level, LRRT2, was defined as a 20 percent reduction in rolling resistance from a base tire. LRRT2 was associated with more advanced approaches such as use of advanced materials and complete tire redesign. As discussed in the Draft TAR, the 2015 NAS report generally supported the cost, effectiveness, and feasibility assumptions for both a 10 and 20 percent reduction in rolling resistance as being appropriate for the 2020 to 2025 time frame.

In Chapter 2.2.6 of this TSD, EPA reviewed the current state of low rolling resistance tire technology and considered developments and trends relating to the feasibility of achieving these levels of reduction. This review showed that tire manufacturers are aggressively pursuing rolling resistance technology, that tires exist today that are achieving these levels of reduction, and that manufacturers are increasingly specifying such tires as original equipment. Although there is some evidence that consumers have associated low rolling resistance technology with lower traction, there is also evidence that tire designers have a significant degree of control over the relationship between the two attributes, and that tires have been designed that are capable of delivering both.

At the time of the FRM, EPA met with a number of the largest tire suppliers in the United States to analyze the feasibility and cost for LRRT2. The suppliers were generally optimistic about the ability to reduce tire rolling resistance in the future without the need to sacrifice traction (safety) or tread life (durability). Suppliers all generally stated that rolling resistance levels could be reduced by 20 percent relative to then-current tires by MY2017. As such, for the FRM analysis, EPA assumed LRRT2 would be initially available in MY2017, but not widespread in the marketplace until MYs 2022-2023. In alignment with that timeframe for introducing new technology, EPA has maintained the Draft TAR's limitation of the phase-in schedule to 75 percent of a manufacturer's fleet in 2021, allowing complete application (100 percent of a manufacturer's fleet) by 2025.

In comments on the Draft TAR, the Alliance and Ford pointed out that "low rolling resistance tires are increasingly specified by OEMs in new vehicles," yet EPA had not accounted for this existing penetration of this technology in the baseline fleet. EPA agrees that tire rolling resistance reductions have been achieved in some MY2015 vehicles relative to the levels in MY2008-2010 vehicles that were used as the null technology point of reference for the FRM and Draft TAR. Furthermore, EPA agrees with the commenters that it is appropriate to account for tire rolling resistance reductions already present in the baseline fleet in order to avoid overestimating the amount of additional improvement that can be achieved at a given cost. Therefore, for this Proposed Determination, EPA has estimated the levels of tire rolling resistance reduction already present in MY2015, and assigned one of three tire rolling resistance levels to each vehicle in the baseline fleet. The process for determining the levels of LRRT0, LRRT1, and LRRT2 is described below.

Using the test weight and road load coefficient data submitted to EPA for compliance certification by manufactures, along the assumptions for brake, hub, and driveline drag described in Appendix B.2.6, EPA estimated a value for the coefficient of tire rolling resistance (C_{TRR}) for each vehicle in the MY2015 fleet.

In this Proposed Determination, LRRT1 remains defined as a 10 percent reduction in rolling resistance from a base tire, and is estimated to result in a 1.9 percent effectiveness improvement for all vehicle classes. Similarly, LRRT2 remains defined as a 20 percent reduction in rolling resistance from a base tire, and is estimated to result in a 3.9 percent effectiveness improvement.

Costs associated with lower rolling resistance tires are equivalent to those used in the Draft TAR except, updated to 2015 dollars. The LRRT costs are shown below.

Table 2.143 Costs for Lower Rolling Resistance Tires (dollar values in 2015$)

Tech	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
LRRT1	DMC	$6	1	$6	$6	$6	$6	$6	$6	$6	$6	$6
LRRT1	IC	Low2	2018	$1	$1	$1	$1	$1	$1	$1	$1	$1
LRRT1	TC			$7	$7	$7	$7	$7	$7	$7	$7	$7
LRRT2	DMC	$44	32	$57	$55	$53	$51	$49	$48	$47	$46	$45
LRRT2	IC	Low2	2024	$11	$11	$11	$11	$11	$11	$11	$11	$8
LRRT2	TC			$68	$66	$64	$62	$60	$59	$57	$56	$53

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs; both levels of lower rolling resistance are incremental to today's baseline tires.

2.3.4.6 Mass Reduction: Data and Assumptions for this Assessment

With several exceptions (which are noted below), for this Proposed Determination analysis, EPA continues to model mass reduction technology using largely the same assumptions that were applied in the Draft TAR analysis.

Specifically, EPA has continued to apply the mass reduction cost estimates that were applied in the Draft TAR, updated to 2015 dollars. These costs continue to be based on the cost curves that were developed and fully described in the Draft TAR. We have also continued to apply the effectiveness values that were applied in the Draft TAR analysis. Finally, we have also used the same method for representing mass reduction in the baseline fleet.

These assumptions and methodologies, and their background, were fully documented in the Draft TAR. For a detailed discussion of the research, methodologies, cost curves, and other analysis performed in the development of these assumptions for the Draft TAR, which continue to be used in the present analysis, please refer to Section 5.3.4.6 of the Draft TAR, "Mass Reduction: Data and Assumptions for this Assessment," which begins on page 5-365 of the Draft TAR.

In this TSD, the present chapter is devoted to highlighting the key updates to the consideration of mass reduction technology that apply uniquely to this Proposed Determination analysis. Section 2.3.4.6.1 includes a description of specific updates, and discussion of some key comments received on the Draft TAR that relate to mass reduction. Section 2.3.4.6.2 reports the mass reduction costs used in OMEGA, updated to 2015 dollars.

2.3.4.6.1 Updates to Mass Reduction for the Current Analysis

Several updates apply to the treatment of mass reduction technology in this Proposed Determination analysis.

First, as described in Chapter 1, the baseline fleet for the Proposed Determination has been updated to MY2015. It should therefore be noted that in referencing the Draft TAR documentation, references to the MY2014 baseline fleet should be understood as representing the MY2015 baseline fleet when interpreted with reference to the present analysis.

Certain updates have also been made to the way mass reduction is represented for pickup trucks in the baseline fleet. In the Draft TAR, EPA's analysis assigned levels of mass reduction specific to each vehicle in the baseline fleet in order to account for variation between current vehicles in the cost and feasibility of achieving additional mass reduction. This was achieved by comparing the 2008 and 2014 versions of each model according to the sales weighted average curb weights of the various trim levels after adjusting for changes in size, additional safety requirements, and drive type. This same methodology was again used for this Proposed Determination assessment, applied to the updated MY2015 baseline fleet.

Although EPA did not receive specific comments on the characterization of mass reduction for pickup trucks in the baseline fleet, EPA has refined the tracking of the pickup truck lineages over time for this Proposed Determination assessment in order to better characterize the cost and feasibility of additional mass reduction for these vehicles.

Unlike passenger cars, light-duty pickup trucks are produced with a variety of cabin and bed configurations, and the mix of the configurations produced often varies from year to year. The model-level approach used in the Draft TAR did not distinguish the change in mass that occurred due to shifts in the production shares of the various pickup truck configurations from the changes in mass that occurred within a given configuration. For example, using the Draft TAR approach, a greater proportion of crew cab configurations in MY2015 would be reflected as an increase in curb weight from MY2008, even if the MY2015 vehicle was lighter than the corresponding configuration in MY2008. For this Proposed Determination assessment, EPA has estimated the amount of mass reduction for pickup trucks in the baseline fleet by comparing curb weights (with adjustments for size, safety equipment, and drive type) for corresponding cab configurations in MYs 2008 and 2015, thereby minimizing the influence of shifts in production shares of the various configurations over that period.

The AAM and Ford commented that EPA had not properly accounted for the amount of mass reduction already implemented in the 2008 MY baseline fleet. Furthermore, AAM acknowledged that manufacturers have adopted lightweight materials, but that has not necessarily resulted in a change in vehicle curb weight due to the addition of other vehicle features. EPA agrees that in many cases, vehicle manufacturers have adopted lightweight materials in the 2014 MY fleet used for the Draft TAR analysis and in the 2015 MY fleet used for the current analysis. For the 2012 FRM, the EPA assumed that all vehicles were starting from the same potential to reduce mass. EPA's method for both the Draft TAR and this Proposed Determination considers differences between vehicles in the incremental cost and feasibility of additional mass reduction.

A comment by AAM addressed mass assessment for 4WD/AWD vehicles. In the Draft TAR, EPA referred to a study performed for Transport Canada which included the evaluation of mass differences in AWD vs. 2WD versions of three different vehicle models (Jeep Cherokee, Ford Fusion and VW Tiguan). The mass differences were 135kg, 72kg, and 78kg respectively for an average of 95kg or 209lbs. A value of 200lbs was used to provide an adjustment to minimize the influence of this vehicle characterization difference in the baseline sales weighted curb weight.[625] AAM commented that the selection of these three vehicles did not "represent typical 4WD/AWD systems," and suggested that EPA use a different source, such as the certification database, to determine the mass increase due to AWD and 4WD systems. EPA disagrees that the mass impact of AWD/4WD systems is not adequately captured. The Jeep Cherokee and the VW Tiguan represent one of the largest and fastest growing segments in the light-duty market. While this weight may under-represent some of the largest 4WD vehicles, it may also over-represent some of the smallest AWD vehicles. For this Proposed Determination EPA has maintained the methodology found in the Draft TAR for assessing the mass impact of AWD and 4WD.

FCA commented that the effectiveness estimates made by EPA for mass reduction were not accurate due to the lack of consideration of Equivalent Weight (ETW) class bins and their effect on fuel economy testing. FCA recommended that EPA adjust its modeling so that mass reduction benefits are only reflected in changes to ETW. EPA does not agree with this recommendation. The average mass reduction projected in the Proposed Determination is approximately 9 percent. This amount of mass reduction will move many vehicles in the fleet down by one or two ETW bins. EPA's approach of allowing mass reduction in continuous increments (actually 0.5 percent increments in the OMEGA analysis) does not cause a systemic underestimation of costs, since cases where manufacturers may be getting less benefit from mass reduction than projected in our analysis would be offset by other cases where manufacturers may be getting more benefit.

2.3.4.6.2 Mass Reduction Costs used in OMEGA

The tables below show an excerpt of the mass reduction costs used in OMEGA. The costs presented here are equivalent to those used in the Draft TAR, updated to 2015 dollars. One notable exception is the expansion in the number of vehicle types relative to the Draft TAR analysis. We discuss the new vehicle types in Section 2.3.1.4 of this TSD. There are 8 tables that follow, with the first four showing mass reduction costs at 5 percent, then 10 percent, then 15 percent then 20 percent mass reduction for the 24 vehicle types that use the car cost curve. The next four tables show mass reduction costs at 5 percent, then 10 percent, then 15 percent then 20 percent mass reduction for the 5 vehicle types that use the truck cost curve. The direct manufacturing costs (DMC), indirect costs (IC, using ICMs) and the total costs (TC) are shown along with the sales weighted average curb weight of all vehicles mapped into the indicated vehicle types, the complexity levels used for indirect costs and the learning curve factor used as discussed in Section 2.3.2.

An important thing to note in the way mass reduction costs are calculated in OMEGA is the differential nature of the calculation. For example, if we focus on vehicle type 1 and assume that a baseline vehicle, of vehicle type 1, has 5 percent mass reduction. That vehicle would have a cost save, relative to null, of $112 (-$112, see Table 2.144, Total Cost (TC) entry for MY2025). If that vehicle were to move to a 10 percent mass reduction, the cost save at that level would be $20 (-$20, see Table 2.145, Total Cost (TC) entry for MY2025). However, the incremental cost for that move, from 5 percent to 10 percent mass reduction, would be (-$20) - (-$120) = $100. In other words, the cost of moving from 5 percent to 10 percent mass reduction for that vehicle would be calculated by OMEGA as a $100 cost increase. All costs shown in the mass reduction cost tables that follow should be taken as relative to the null vehicle. As a result, the cost for 10 percent mass reduction for this example vehicle having 5 percent mass reduction in the baseline, would be $100 and not -$20.

Table 2.144 Costs for 5 Percent Mass Reduction for Vehicle Types using the Car Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2772	30	-$162	-$157	-$153	-$149	-$145	-$142	-$139	-$137	-$135
2	DMC	2988	30	-$175	-$169	-$165	-$160	-$157	-$153	-$150	-$148	-$145
3	DMC	3266	30	-$191	-$185	-$180	-$175	-$171	-$168	-$164	-$161	-$159
4	DMC	3323	30	-$195	-$188	-$183	-$178	-$174	-$171	-$167	-$164	-$161

5	DMC	3506	30	-$205	-$199	-$193	-$188	-$184	-$180	-$176	-$173	-$170
6	DMC	3554	30	-$208	-$201	-$196	-$191	-$186	-$182	-$179	-$176	-$173
7	DMC	3928	30	-$230	-$223	-$216	-$211	-$206	-$202	-$198	-$194	-$191
10	DMC	3867	30	-$226	-$219	-$213	-$207	-$203	-$198	-$195	-$191	-$188
11	DMC	4433	30	-$260	-$251	-$244	-$238	-$232	-$227	-$223	-$219	-$215
12	DMC	2976	30	-$174	-$169	-$164	-$160	-$156	-$153	-$150	-$147	-$145
13	DMC	3220	30	-$189	-$183	-$177	-$173	-$169	-$165	-$162	-$159	-$156
14	DMC	3328	30	-$195	-$189	-$183	-$179	-$174	-$171	-$167	-$164	-$162
15	DMC	3510	30	-$206	-$199	-$193	-$188	-$184	-$180	-$177	-$173	-$171
16	DMC	3699	30	-$217	-$210	-$204	-$198	-$194	-$190	-$186	-$183	-$180
17	DMC	3768	30	-$221	-$214	-$207	-$202	-$198	-$193	-$190	-$186	-$183
18	DMC	4011	30	-$235	-$227	-$221	-$215	-$210	-$206	-$202	-$198	-$195
19	DMC	4022	30	-$236	-$228	-$221	-$216	-$211	-$206	-$202	-$199	-$195
20	DMC	4453	30	-$261	-$252	-$245	-$239	-$233	-$229	-$224	-$220	-$216
21	DMC	4610	30	-$270	-$261	-$254	-$247	-$242	-$237	-$232	-$228	-$224
23	DMC	5188	30	-$304	-$294	-$286	-$278	-$272	-$266	-$261	-$256	-$252
24	DMC	5678	30	-$333	-$322	-$313	-$305	-$298	-$291	-$286	-$281	-$276
26	DMC	3970	30	-$232	-$225	-$219	-$213	-$208	-$204	-$200	-$196	-$193
27	DMC	4957	30	-$290	-$281	-$273	-$266	-$260	-$254	-$249	-$245	-$241
28	DMC	5328	30	-$312	-$302	-$293	-$286	-$279	-$273	-$268	-$263	-$259
1	IC	Low2	2024	$28	$28	$28	$28	$28	$28	$28	$28	$23
2	IC	Low2	2024	$31	$31	$31	$31	$31	$31	$31	$31	$25
3	IC	Low2	2024	$33	$33	$33	$33	$33	$33	$33	$33	$27
4	IC	Low2	2024	$34	$34	$34	$34	$34	$34	$34	$34	$27
5	IC	Low2	2024	$36	$36	$36	$36	$36	$36	$36	$36	$29
6	IC	Low2	2024	$36	$36	$36	$36	$36	$36	$36	$36	$29
7	IC	Low2	2024	$40	$40	$40	$40	$40	$40	$40	$40	$32
10	IC	Low2	2024	$39	$39	$39	$39	$39	$39	$39	$39	$32
11	IC	Low2	2024	$45	$45	$45	$45	$45	$45	$45	$45	$37
12	IC	Low2	2024	$30	$30	$30	$30	$30	$30	$30	$30	$25
13	IC	Low2	2024	$33	$33	$33	$33	$33	$33	$33	$33	$27
14	IC	Low2	2024	$34	$34	$34	$34	$34	$34	$34	$34	$27
15	IC	Low2	2024	$36	$36	$36	$36	$36	$36	$36	$36	$29
16	IC	Low2	2024	$38	$38	$38	$38	$38	$38	$38	$38	$30
17	IC	Low2	2024	$38	$38	$38	$38	$38	$38	$38	$38	$31
18	IC	Low2	2024	$41	$41	$41	$41	$41	$41	$41	$41	$33
19	IC	Low2	2024	$41	$41	$41	$41	$41	$41	$41	$41	$33
20	IC	Low2	2024	$45	$45	$45	$45	$45	$45	$45	$45	$37
21	IC	Low2	2024	$47	$47	$47	$47	$47	$47	$47	$47	$38
23	IC	Low2	2024	$53	$53	$53	$53	$53	$53	$53	$53	$43
24	IC	Low2	2024	$58	$58	$58	$58	$58	$58	$58	$58	$47
26	IC	Low2	2024	$41	$41	$41	$41	$41	$41	$41	$41	$33
27	IC	Low2	2024	$51	$51	$51	$51	$51	$51	$51	$51	$41
28	IC	Low2	2024	$54	$54	$54	$54	$54	$54	$54	$54	$44
1	TC			-$134	-$129	-$124	-$120	-$117	-$114	-$111	-$109	-$112
2	TC			-$144	-$139	-$134	-$130	-$126	-$123	-$120	-$117	-$121
3	TC			-$158	-$152	-$147	-$142	-$138	-$134	-$131	-$128	-$132
4	TC			-$161	-$154	-$149	-$144	-$140	-$137	-$133	-$130	-$134
5	TC			-$170	-$163	-$157	-$152	-$148	-$144	-$141	-$137	-$141
6	TC			-$172	-$165	-$159	-$154	-$150	-$146	-$143	-$139	-$143
7	TC			-$190	-$183	-$176	-$171	-$166	-$161	-$158	-$154	-$159
10	TC			-$187	-$180	-$173	-$168	-$163	-$159	-$155	-$152	-$156
11	TC			-$214	-$206	-$199	-$193	-$187	-$182	-$178	-$174	-$179
12	TC			-$144	-$138	-$133	-$129	-$126	-$122	-$119	-$117	-$120
13	TC			-$156	-$150	-$144	-$140	-$136	-$132	-$129	-$126	-$130
14	TC			-$161	-$155	-$149	-$145	-$140	-$137	-$133	-$130	-$134
15	TC			-$170	-$163	-$157	-$153	-$148	-$144	-$141	-$138	-$142
16	TC			-$179	-$172	-$166	-$161	-$156	-$152	-$148	-$145	-$149
17	TC			-$182	-$175	-$169	-$164	-$159	-$155	-$151	-$148	-$152
18	TC			-$194	-$186	-$180	-$174	-$169	-$165	-$161	-$157	-$162
19	TC			-$194	-$187	-$180	-$175	-$170	-$165	-$161	-$158	-$162
20	TC			-$215	-$207	-$200	-$193	-$188	-$183	-$179	-$175	-$180
21	TC			-$223	-$214	-$207	-$200	-$195	-$189	-$185	-$181	-$186

23	TC			-$251	-$241	-$233	-$225	-$219	-$213	-$208	-$203	-$209
24	TC			-$275	-$264	-$255	-$247	-$240	-$233	-$228	-$223	-$229
26	TC			-$192	-$184	-$178	-$172	-$168	-$163	-$159	-$156	-$160
27	TC			-$240	-$230	-$222	-$215	-$209	-$204	-$199	-$194	-$200
28	TC			-$258	-$248	-$239	-$232	-$225	-$219	-$214	-$209	-$215

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.145 Costs for 10 Percent Mass Reduction for Vehicle Types using the Car Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2772	30	-$134	-$130	-$126	-$123	-$120	-$117	-$115	-$113	-$111
2	DMC	2988	30	-$144	-$140	-$136	-$132	-$129	-$127	-$124	-$122	-$120
3	DMC	3266	30	-$158	-$153	-$148	-$145	-$141	-$138	-$136	-$133	-$131
4	DMC	3323	30	-$161	-$155	-$151	-$147	-$144	-$141	-$138	-$135	-$133
5	DMC	3506	30	-$169	-$164	-$159	-$155	-$152	-$148	-$146	-$143	-$141
6	DMC	3554	30	-$172	-$166	-$161	-$157	-$154	-$150	-$148	-$145	-$142
7	DMC	3928	30	-$190	-$184	-$178	-$174	-$170	-$166	-$163	-$160	-$157
10	DMC	3867	30	-$187	-$181	-$176	-$171	-$167	-$164	-$161	-$158	-$155
11	DMC	4433	30	-$214	-$207	-$201	-$196	-$192	-$188	-$184	-$181	-$178
12	DMC	2976	30	-$144	-$139	-$135	-$132	-$129	-$126	-$124	-$121	-$119
13	DMC	3220	30	-$156	-$151	-$146	-$143	-$139	-$136	-$134	-$131	-$129
14	DMC	3328	30	-$161	-$156	-$151	-$147	-$144	-$141	-$138	-$136	-$133
15	DMC	3510	30	-$170	-$164	-$159	-$155	-$152	-$149	-$146	-$143	-$141
16	DMC	3699	30	-$179	-$173	-$168	-$164	-$160	-$157	-$154	-$151	-$148
17	DMC	3768	30	-$182	-$176	-$171	-$167	-$163	-$160	-$156	-$154	-$151
18	DMC	4011	30	-$194	-$188	-$182	-$178	-$173	-$170	-$167	-$164	-$161
19	DMC	4022	30	-$194	-$188	-$183	-$178	-$174	-$170	-$167	-$164	-$161
20	DMC	4453	30	-$215	-$208	-$202	-$197	-$193	-$189	-$185	-$182	-$178
21	DMC	4610	30	-$223	-$216	-$209	-$204	-$199	-$195	-$191	-$188	-$185
23	DMC	5188	30	-$251	-$243	-$236	-$230	-$224	-$220	-$215	-$212	-$208
24	DMC	5678	30	-$274	-$265	-$258	-$251	-$246	-$240	-$236	-$231	-$228
26	DMC	3970	30	-$192	-$186	-$180	-$176	-$172	-$168	-$165	-$162	-$159
27	DMC	4957	30	-$239	-$232	-$225	-$219	-$214	-$210	-$206	-$202	-$199
28	DMC	5328	30	-$257	-$249	-$242	-$236	-$230	-$226	-$221	-$217	-$214
1	IC	Low2	2024	$113	$113	$113	$113	$113	$113	$113	$113	$91
2	IC	Low2	2024	$122	$122	$122	$122	$122	$122	$122	$122	$98
3	IC	Low2	2024	$133	$133	$133	$133	$133	$133	$133	$133	$108
4	IC	Low2	2024	$136	$136	$136	$136	$136	$136	$136	$136	$110
5	IC	Low2	2024	$143	$143	$143	$143	$143	$143	$143	$143	$116
6	IC	Low2	2024	$145	$145	$145	$145	$145	$145	$145	$145	$117
7	IC	Low2	2024	$160	$160	$160	$160	$160	$160	$160	$160	$129
10	IC	Low2	2024	$158	$158	$158	$158	$158	$158	$158	$158	$127
11	IC	Low2	2024	$181	$181	$181	$181	$181	$181	$181	$181	$146
12	IC	Low2	2024	$122	$122	$122	$122	$122	$122	$122	$122	$98
13	IC	Low2	2024	$132	$132	$132	$132	$132	$132	$132	$132	$106
14	IC	Low2	2024	$136	$136	$136	$136	$136	$136	$136	$136	$110
15	IC	Low2	2024	$143	$143	$143	$143	$143	$143	$143	$143	$116
16	IC	Low2	2024	$151	$151	$151	$151	$151	$151	$151	$151	$122
17	IC	Low2	2024	$154	$154	$154	$154	$154	$154	$154	$154	$124
18	IC	Low2	2024	$164	$164	$164	$164	$164	$164	$164	$164	$132
19	IC	Low2	2024	$164	$164	$164	$164	$164	$164	$164	$164	$133
20	IC	Low2	2024	$182	$182	$182	$182	$182	$182	$182	$182	$147
21	IC	Low2	2024	$188	$188	$188	$188	$188	$188	$188	$188	$152
23	IC	Low2	2024	$212	$212	$212	$212	$212	$212	$212	$212	$171
24	IC	Low2	2024	$232	$232	$232	$232	$232	$232	$232	$232	$187
26	IC	Low2	2024	$162	$162	$162	$162	$162	$162	$162	$162	$131
27	IC	Low2	2024	$203	$203	$203	$203	$203	$203	$203	$203	$163
28	IC	Low2	2024	$218	$218	$218	$218	$218	$218	$218	$218	$176

1	TC			-$21	-$16	-$13	-$9	-$7	-$4	-$2	$0	-$20
2	TC			-$22	-$18	-$14	-$10	-$7	-$4	-$2	$0	-$21
3	TC			-$24	-$19	-$15	-$11	-$8	-$5	-$2	$0	-$23
4	TC			-$25	-$20	-$15	-$11	-$8	-$5	-$2	$0	-$24
5	TC			-$26	-$21	-$16	-$12	-$8	-$5	-$2	$0	-$25
6	TC			-$27	-$21	-$16	-$12	-$9	-$5	-$2	$0	-$25
7	TC			-$29	-$23	-$18	-$13	-$9	-$6	-$3	$0	-$28
10	TC			-$29	-$23	-$18	-$13	-$9	-$6	-$3	$0	-$28
11	TC			-$33	-$26	-$20	-$15	-$11	-$7	-$3	$0	-$32
12	TC			-$22	-$18	-$14	-$10	-$7	-$4	-$2	$0	-$21
13	TC			-$24	-$19	-$15	-$11	-$8	-$5	-$2	$0	-$23
14	TC			-$25	-$20	-$15	-$11	-$8	-$5	-$2	$0	-$24
15	TC			-$26	-$21	-$16	-$12	-$8	-$5	-$2	$0	-$25
16	TC			-$28	-$22	-$17	-$13	-$9	-$5	-$2	$0	-$26
17	TC			-$28	-$22	-$17	-$13	-$9	-$6	-$2	$0	-$27
18	TC			-$30	-$24	-$18	-$14	-$10	-$6	-$3	$0	-$29
19	TC			-$30	-$24	-$18	-$14	-$10	-$6	-$3	$0	-$29
20	TC			-$33	-$26	-$20	-$15	-$11	-$7	-$3	$0	-$32
21	TC			-$34	-$27	-$21	-$16	-$11	-$7	-$3	$0	-$33
23	TC			-$39	-$31	-$24	-$18	-$12	-$8	-$3	$0	-$37
24	TC			-$42	-$34	-$26	-$19	-$14	-$8	-$4	$0	-$40
26	TC			-$30	-$23	-$18	-$14	-$10	-$6	-$3	$0	-$28
27	TC			-$37	-$29	-$23	-$17	-$12	-$7	-$3	$0	-$35
28	TC			-$40	-$31	-$24	-$18	-$13	-$8	-$4	$0	-$38

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.146 Costs for 15 Percent Mass Reduction for Vehicle Types using the Car Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2772	30	-$34	-$32	-$32	-$31	-$30	-$29	-$29	-$28	-$28
2	DMC	2988	30	-$36	-$35	-$34	-$33	-$32	-$32	-$31	-$30	-$30
3	DMC	3266	30	-$39	-$38	-$37	-$36	-$35	-$35	-$34	-$33	-$33
4	DMC	3323	30	-$40	-$39	-$38	-$37	-$36	-$35	-$35	-$34	-$33
5	DMC	3506	30	-$42	-$41	-$40	-$39	-$38	-$37	-$36	-$36	-$35
6	DMC	3554	30	-$43	-$42	-$40	-$39	-$38	-$38	-$37	-$36	-$36
7	DMC	3928	30	-$47	-$46	-$45	-$44	-$43	-$42	-$41	-$40	-$39
10	DMC	3867	30	-$47	-$45	-$44	-$43	-$42	-$41	-$40	-$39	-$39
11	DMC	4433	30	-$54	-$52	-$50	-$49	-$48	-$47	-$46	-$45	-$44
12	DMC	2976	30	-$36	-$35	-$34	-$33	-$32	-$32	-$31	-$30	-$30
13	DMC	3220	30	-$39	-$38	-$37	-$36	-$35	-$34	-$33	-$33	-$32
14	DMC	3328	30	-$40	-$39	-$38	-$37	-$36	-$35	-$35	-$34	-$33
15	DMC	3510	30	-$42	-$41	-$40	-$39	-$38	-$37	-$36	-$36	-$35
16	DMC	3699	30	-$45	-$43	-$42	-$41	-$40	-$39	-$38	-$38	-$37
17	DMC	3768	30	-$46	-$44	-$43	-$42	-$41	-$40	-$39	-$38	-$38
18	DMC	4011	30	-$48	-$47	-$46	-$44	-$43	-$42	-$42	-$41	-$40
19	DMC	4022	30	-$49	-$47	-$46	-$45	-$44	-$43	-$42	-$41	-$40
20	DMC	4453	30	-$54	-$52	-$51	-$49	-$48	-$47	-$46	-$45	-$45
21	DMC	4610	30	-$56	-$54	-$52	-$51	-$50	-$49	-$48	-$47	-$46
23	DMC	5188	30	-$63	-$61	-$59	-$57	-$56	-$55	-$54	-$53	-$52
24	DMC	5678	30	-$69	-$66	-$65	-$63	-$61	-$60	-$59	-$58	-$57
26	DMC	3970	30	-$48	-$46	-$45	-$44	-$43	-$42	-$41	-$40	-$40
27	DMC	4957	30	-$60	-$58	-$56	-$55	-$54	-$53	-$51	-$51	-$50
28	DMC	5328	30	-$64	-$62	-$61	-$59	-$58	-$56	-$55	-$54	-$53
1	IC	Low2	2024	$255	$255	$255	$255	$255	$255	$255	$255	$206
2	IC	Low2	2024	$275	$275	$275	$275	$275	$275	$275	$275	$222
3	IC	Low2	2024	$300	$300	$300	$300	$300	$300	$300	$300	$242
4	IC	Low2	2024	$305	$305	$305	$305	$305	$305	$305	$305	$246

5	IC	Low2	2024	$322	$322	$322	$322	$322	$322	$322	$322	$260
6	IC	Low2	2024	$327	$327	$327	$327	$327	$327	$327	$327	$263
7	IC	Low2	2024	$361	$361	$361	$361	$361	$361	$361	$361	$291
10	IC	Low2	2024	$355	$355	$355	$355	$355	$355	$355	$355	$287
11	IC	Low2	2024	$407	$407	$407	$407	$407	$407	$407	$407	$329
12	IC	Low2	2024	$274	$274	$274	$274	$274	$274	$274	$274	$221
13	IC	Low2	2024	$296	$296	$296	$296	$296	$296	$296	$296	$239
14	IC	Low2	2024	$306	$306	$306	$306	$306	$306	$306	$306	$247
15	IC	Low2	2024	$323	$323	$323	$323	$323	$323	$323	$323	$260
16	IC	Low2	2024	$340	$340	$340	$340	$340	$340	$340	$340	$274
17	IC	Low2	2024	$346	$346	$346	$346	$346	$346	$346	$346	$279
18	IC	Low2	2024	$369	$369	$369	$369	$369	$369	$369	$369	$297
19	IC	Low2	2024	$370	$370	$370	$370	$370	$370	$370	$370	$298
20	IC	Low2	2024	$409	$409	$409	$409	$409	$409	$409	$409	$330
21	IC	Low2	2024	$424	$424	$424	$424	$424	$424	$424	$424	$342
23	IC	Low2	2024	$477	$477	$477	$477	$477	$477	$477	$477	$385
24	IC	Low2	2024	$522	$522	$522	$522	$522	$522	$522	$522	$421
26	IC	Low2	2024	$365	$365	$365	$365	$365	$365	$365	$365	$294
27	IC	Low2	2024	$456	$456	$456	$456	$456	$456	$456	$456	$368
28	IC	Low2	2024	$490	$490	$490	$490	$490	$490	$490	$490	$395
1	TC			$221	$222	$223	$224	$225	$225	$226	$227	$178
2	TC			$239	$240	$241	$242	$242	$243	$244	$244	$192
3	TC			$261	$262	$263	$264	$265	$266	$266	$267	$209
4	TC			$265	$267	$268	$269	$269	$270	$271	$272	$213
5	TC			$280	$281	$282	$283	$284	$285	$286	$286	$225
6	TC			$284	$285	$286	$287	$288	$289	$290	$290	$228
7	TC			$314	$315	$316	$318	$319	$319	$320	$321	$252
10	TC			$309	$310	$311	$313	$314	$314	$315	$316	$248
11	TC			$354	$356	$357	$358	$359	$360	$361	$362	$284
12	TC			$238	$239	$240	$241	$241	$242	$243	$243	$191
13	TC			$257	$258	$259	$260	$261	$262	$263	$263	$206
14	TC			$266	$267	$268	$269	$270	$271	$271	$272	$213
15	TC			$280	$282	$283	$284	$285	$285	$286	$287	$225
16	TC			$295	$297	$298	$299	$300	$301	$302	$302	$237
17	TC			$301	$302	$304	$305	$306	$306	$307	$308	$242
18	TC			$320	$322	$323	$324	$325	$326	$327	$328	$257
19	TC			$321	$323	$324	$325	$326	$327	$328	$329	$258
20	TC			$355	$357	$359	$360	$361	$362	$363	$364	$286
21	TC			$368	$370	$371	$373	$374	$375	$376	$377	$296
23	TC			$414	$416	$418	$419	$421	$422	$423	$424	$333
24	TC			$453	$455	$457	$459	$460	$462	$463	$464	$364
26	TC			$317	$318	$320	$321	$322	$323	$324	$324	$255
27	TC			$396	$398	$399	$401	$402	$403	$404	$405	$318
28	TC			$425	$427	$429	$431	$432	$433	$434	$435	$342

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.147 Costs for 20 Percent Mass Reduction for Vehicle Types using the Car Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	2772	30	$114	$110	$107	$104	$102	$100	$98	$96	$94
2	DMC	2988	30	$123	$119	$115	$112	$110	$107	$105	$103	$102
3	DMC	3266	30	$134	$130	$126	$123	$120	$117	$115	$113	$111
4	DMC	3323	30	$136	$132	$128	$125	$122	$119	$117	$115	$113
5	DMC	3506	30	$144	$139	$135	$132	$129	$126	$124	$121	$119
6	DMC	3554	30	$146	$141	$137	$134	$130	$128	$125	$123	$121
7	DMC	3928	30	$161	$156	$151	$148	$144	$141	$138	$136	$134
10	DMC	3867	30	$159	$153	$149	$145	$142	$139	$136	$134	$132

11	DMC	4433	30	$182	$176	$171	$167	$163	$159	$156	$153	$151
12	DMC	2976	30	$122	$118	$115	$112	$109	$107	$105	$103	$101
13	DMC	3220	30	$132	$128	$124	$121	$118	$116	$113	$111	$110
14	DMC	3328	30	$136	$132	$128	$125	$122	$120	$117	$115	$113
15	DMC	3510	30	$144	$139	$135	$132	$129	$126	$124	$121	$119
16	DMC	3699	30	$152	$147	$143	$139	$136	$133	$130	$128	$126
17	DMC	3768	30	$154	$150	$145	$142	$138	$135	$133	$130	$128
18	DMC	4011	30	$164	$159	$155	$151	$147	$144	$141	$139	$136
19	DMC	4022	30	$165	$160	$155	$151	$148	$145	$142	$139	$137
20	DMC	4453	30	$183	$177	$172	$167	$163	$160	$157	$154	$151
21	DMC	4610	30	$189	$183	$178	$173	$169	$166	$162	$160	$157
23	DMC	5188	30	$213	$206	$200	$195	$190	$186	$183	$180	$177
24	DMC	5678	30	$233	$225	$219	$213	$208	$204	$200	$196	$193
26	DMC	3970	30	$163	$158	$153	$149	$146	$143	$140	$137	$135
27	DMC	4957	30	$203	$197	$191	$186	$182	$178	$175	$172	$169
28	DMC	5328	30	$218	$211	$205	$200	$196	$191	$188	$184	$181
1	IC	Low2	2024	$453	$453	$453	$453	$453	$453	$453	$453	$365
2	IC	Low2	2024	$488	$488	$488	$488	$488	$488	$488	$488	$394
3	IC	Low2	2024	$534	$534	$534	$534	$534	$534	$534	$534	$431
4	IC	Low2	2024	$543	$543	$543	$543	$543	$543	$543	$543	$438
5	IC	Low2	2024	$573	$573	$573	$573	$573	$573	$573	$573	$462
6	IC	Low2	2024	$581	$581	$581	$581	$581	$581	$581	$581	$468
7	IC	Low2	2024	$642	$642	$642	$642	$642	$642	$642	$642	$518
10	IC	Low2	2024	$632	$632	$632	$632	$632	$632	$632	$632	$510
11	IC	Low2	2024	$724	$724	$724	$724	$724	$724	$724	$724	$584
12	IC	Low2	2024	$486	$486	$486	$486	$486	$486	$486	$486	$392
13	IC	Low2	2024	$526	$526	$526	$526	$526	$526	$526	$526	$424
14	IC	Low2	2024	$544	$544	$544	$544	$544	$544	$544	$544	$439
15	IC	Low2	2024	$574	$574	$574	$574	$574	$574	$574	$574	$463
16	IC	Low2	2024	$604	$604	$604	$604	$604	$604	$604	$604	$488
17	IC	Low2	2024	$616	$616	$616	$616	$616	$616	$616	$616	$497
18	IC	Low2	2024	$656	$656	$656	$656	$656	$656	$656	$656	$529
19	IC	Low2	2024	$657	$657	$657	$657	$657	$657	$657	$657	$530
20	IC	Low2	2024	$728	$728	$728	$728	$728	$728	$728	$728	$587
21	IC	Low2	2024	$753	$753	$753	$753	$753	$753	$753	$753	$608
23	IC	Low2	2024	$848	$848	$848	$848	$848	$848	$848	$848	$684
24	IC	Low2	2024	$928	$928	$928	$928	$928	$928	$928	$928	$748
26	IC	Low2	2024	$649	$649	$649	$649	$649	$649	$649	$649	$523
27	IC	Low2	2024	$810	$810	$810	$810	$810	$810	$810	$810	$653
28	IC	Low2	2024	$871	$871	$871	$871	$871	$871	$871	$871	$702
1	TC			$567	$563	$560	$557	$555	$553	$551	$549	$460
2	TC			$611	$607	$603	$601	$598	$596	$594	$592	$496
3	TC			$668	$663	$660	$657	$654	$651	$649	$647	$542
4	TC			$679	$675	$671	$668	$665	$662	$660	$658	$551
5	TC			$717	$712	$708	$705	$702	$699	$696	$694	$581
6	TC			$726	$722	$718	$714	$711	$708	$706	$704	$589
7	TC			$803	$798	$793	$790	$786	$783	$780	$778	$651
10	TC			$790	$785	$781	$777	$774	$771	$768	$766	$641
11	TC			$906	$900	$895	$891	$887	$884	$881	$878	$735
12	TC			$608	$604	$601	$598	$596	$593	$591	$589	$494
13	TC			$658	$654	$650	$647	$644	$642	$640	$638	$534
14	TC			$680	$676	$672	$669	$666	$663	$661	$659	$552
15	TC			$718	$713	$709	$705	$702	$700	$697	$695	$582
16	TC			$756	$751	$747	$743	$740	$737	$735	$732	$613
17	TC			$770	$765	$761	$757	$754	$751	$748	$746	$625
18	TC			$820	$815	$810	$806	$803	$800	$797	$794	$665
19	TC			$822	$817	$812	$808	$805	$802	$799	$796	$667
20	TC			$910	$904	$899	$895	$891	$888	$885	$882	$738
21	TC			$942	$936	$931	$927	$923	$919	$916	$913	$764
23	TC			$1,061	$1,054	$1,048	$1,043	$1,038	$1,034	$1,031	$1,027	$860
24	TC			$1,161	$1,153	$1,147	$1,141	$1,136	$1,132	$1,128	$1,124	$942
26	TC			$811	$806	$802	$798	$794	$791	$789	$786	$658
27	TC			$1,013	$1,007	$1,001	$996	$992	$988	$985	$982	$822

28	TC			$1,089	$1,082	$1,076	$1,071	$1,066	$1,062	$1,058	$1,055	$884

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.148 Costs for 5 Percent Mass Reduction for Vehicle Types using the Truck Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4016	30	-$216	-$209	-$203	-$198	-$193	-$189	-$185	-$182	-$179
9	DMC	4976	30	-$267	-$259	-$251	-$245	-$239	-$234	-$230	-$226	-$222
22	DMC	4214	30	-$226	-$219	-$213	-$208	-$203	-$198	-$195	-$191	-$188
25	DMC	5106	30	-$274	-$266	-$258	-$251	-$246	-$240	-$236	-$232	-$228
29	DMC	4883	30	-$262	-$254	-$247	-$240	-$235	-$230	-$225	-$221	-$218
8	IC	Low2	2024	$62	$62	$62	$62	$62	$62	$62	$62	$50
9	IC	Low2	2024	$77	$77	$77	$77	$77	$77	$77	$77	$62
22	IC	Low2	2024	$65	$65	$65	$65	$65	$65	$65	$65	$53
25	IC	Low2	2024	$79	$79	$79	$79	$79	$79	$79	$79	$64
29	IC	Low2	2024	$75	$75	$75	$75	$75	$75	$75	$75	$61
8	TC			-$154	-$147	-$141	-$136	-$131	-$127	-$123	-$120	-$129
9	TC			-$191	-$182	-$175	-$168	-$163	-$157	-$153	-$149	-$160
22	TC			-$161	-$154	-$148	-$142	-$138	-$133	-$130	-$126	-$135
25	TC			-$196	-$187	-$179	-$173	-$167	-$162	-$157	-$153	-$164
29	TC			-$187	-$179	-$171	-$165	-$160	-$155	-$150	-$146	-$157

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.149 Costs for 10 Percent Mass Reduction for Vehicle Types using the Truck Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4016	30	$63	$61	$59	$58	$56	$55	$54	$53	$52
9	DMC	4976	30	$78	$76	$73	$72	$70	$68	$67	$66	$65
22	DMC	4214	30	$66	$64	$62	$61	$59	$58	$57	$56	$55
25	DMC	5106	30	$80	$78	$75	$73	$72	$70	$69	$68	$66
29	DMC	4883	30	$77	$74	$72	$70	$69	$67	$66	$65	$64
8	IC	Low2	2024	$248	$248	$248	$248	$248	$248	$248	$248	$201
9	IC	Low2	2024	$307	$307	$307	$307	$307	$307	$307	$307	$249
22	IC	Low2	2024	$260	$260	$260	$260	$260	$260	$260	$260	$211
25	IC	Low2	2024	$315	$315	$315	$315	$315	$315	$315	$315	$256
29	IC	Low2	2024	$302	$302	$302	$302	$302	$302	$302	$302	$245
8	TC			$311	$309	$307	$306	$304	$303	$302	$301	$253
9	TC			$385	$383	$381	$379	$377	$376	$374	$373	$314
22	TC			$326	$324	$322	$321	$319	$318	$317	$316	$266
25	TC			$395	$393	$391	$389	$387	$385	$384	$383	$322
29	TC			$378	$376	$374	$372	$370	$369	$367	$366	$308

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.150 Costs for 15 Percent Mass Reduction for Vehicle Types using the Truck Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4016	30	$528	$511	$497	$484	$473	$463	$454	$446	$438

9	DMC	4976	30	$655	$634	$616	$600	$586	$574	$563	$552	$543
22	DMC	4214	30	$555	$537	$521	$508	$496	$486	$477	$468	$460
25	DMC	5106	30	$672	$650	$632	$616	$601	$589	$577	$567	$557
29	DMC	4883	30	$643	$622	$604	$589	$575	$563	$552	$542	$533
8	IC	Low2	2024	$558	$558	$558	$558	$558	$558	$558	$558	$453
9	IC	Low2	2024	$691	$691	$691	$691	$691	$691	$691	$691	$561
22	IC	Low2	2024	$586	$586	$586	$586	$586	$586	$586	$586	$475
25	IC	Low2	2024	$709	$709	$709	$709	$709	$709	$709	$709	$576
29	IC	Low2	2024	$678	$678	$678	$678	$678	$678	$678	$678	$550
8	TC			$1,086	$1,069	$1,055	$1,042	$1,031	$1,021	$1,012	$1,004	$891
9	TC			$1,346	$1,325	$1,307	$1,291	$1,277	$1,265	$1,254	$1,244	$1,104
22	TC			$1,140	$1,122	$1,107	$1,094	$1,082	$1,072	$1,062	$1,054	$935
25	TC			$1,381	$1,360	$1,341	$1,325	$1,311	$1,298	$1,287	$1,276	$1,133
29	TC			$1,321	$1,300	$1,283	$1,267	$1,254	$1,241	$1,231	$1,221	$1,083

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

Table 2.151 Costs for 20 Percent Mass Reduction for Vehicle Types using the Truck Cost Curve (2015$)

Vehicle Type	Cost type	DMC: CurbWt IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
8	DMC	4016	30	$1,115	$1,079	$1,049	$1,022	$998	$977	$958	$941	$925
9	DMC	4976	30	$1,382	$1,337	$1,299	$1,266	$1,237	$1,211	$1,187	$1,166	$1,146
22	DMC	4214	30	$1,170	$1,133	$1,100	$1,072	$1,048	$1,026	$1,006	$988	$971
25	DMC	5106	30	$1,418	$1,372	$1,333	$1,299	$1,269	$1,242	$1,218	$1,196	$1,176
29	DMC	4883	30	$1,356	$1,312	$1,275	$1,242	$1,214	$1,188	$1,165	$1,144	$1,125
8	IC	Low2	2024	$992	$992	$992	$992	$992	$992	$992	$992	$805
9	IC	Low2	2024	$1,229	$1,229	$1,229	$1,229	$1,229	$1,229	$1,229	$1,229	$997
22	IC	Low2	2024	$1,041	$1,041	$1,041	$1,041	$1,041	$1,041	$1,041	$1,041	$844
25	IC	Low2	2024	$1,261	$1,261	$1,261	$1,261	$1,261	$1,261	$1,261	$1,261	$1,023
29	IC	Low2	2024	$1,206	$1,206	$1,206	$1,206	$1,206	$1,206	$1,206	$1,206	$978
8	TC			$2,107	$2,071	$2,041	$2,014	$1,990	$1,969	$1,950	$1,933	$1,730
9	TC			$2,611	$2,566	$2,528	$2,495	$2,466	$2,440	$2,416	$2,395	$2,143
22	TC			$2,211	$2,174	$2,141	$2,113	$2,089	$2,066	$2,047	$2,028	$1,815
25	TC			$2,679	$2,633	$2,594	$2,560	$2,530	$2,504	$2,480	$2,458	$2,200
29	TC			$2,562	$2,518	$2,481	$2,449	$2,420	$2,394	$2,371	$2,350	$2,103

Note: DMC=direct manufacturing cost; IC=indirect cost; TC=total cost.

2.3.4.7 Other Vehicle Technologies

2.3.4.7.1 Electrified Power Steering: Data and Assumptions for this Assessment

For the 2017-2025 final rule and Draft TAR, EPA estimated a 1 to 2 percent effectiveness for electrified power steering in light duty vehicles, based on the 2015 NAS report, Sierra Research Report and confidential OEM data. The 2010 Ricardo study also confirmed this estimate. EPA have reviewed these effectiveness estimates and found them to be accurate, thus they have been retained for this Proposed Determination. There were no public comments received with supporting data that would provide basis for a change to the cost or effectiveness estimates for this technology, nor has EPA found additional information that supports such a change since the Draft TAR.

Costs associated with electric power steering are equivalent to those used in the Draft TAR, updated to 2015 dollars. The electric power steering costs incremental to hydraulic power steering are shown below.

Table 2.152 Costs for Electric Power Steering (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$99	24	$94	$92	$91	$89	$88	$87	$85	$84	$83
IC	Low2	2018	$24	$24	$19	$19	$19	$19	$19	$19	$19
TC			$118	$116	$110	$108	$107	$106	$104	$103	$102

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.7.2 Improved Accessories: Data and Assumptions for this Assessment

There were no public comments received with supporting data that would provide basis for a change to the cost or effectiveness estimates for this technology, nor has EPA found additional information that supports such a change since the Draft TAR.

In MYs 2017-2025 final rule and the Draft TAR, EPA used an effectiveness value in the range of 1 to 2 percent.

As in the Draft TAR, for this Proposed Determination assessment, EPA considered two levels of improved accessories. Level 1 of this technology (IACC1) incorporates a high efficiency alternator (70 percent efficiency). The second level of improved accessories (IACC2) adds the higher efficiency alternator and incorporates a mild regenerative alternator strategy, as well as intelligent cooling. EPA used effectiveness values in the 1.2 to 1.8 percent range, varying with vehicle subclass.

Costs associated with improved accessories are equivalent to those used in the Draft TAR, updated to 2015 dollars. The improved accessory costs (levels 1 and 2) are shown below. Cost is higher for improved accessories level 2 due to the inclusion of a higher efficiency alternator and a mild level of regeneration, hence the $40 to $50 higher cost. Both improved accessory costs are incremental to the baseline.

Table 2.153 Costs for Improved Accessories Level 1 (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$80	24	$77	$75	$74	$73	$71	$70	$69	$69	$68
IC	Low2	2018	$19	$19	$15	$15	$15	$15	$15	$15	$15

TC			$96	$95	$89	$88	$87	$86	$85	$84	$83

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Table 2.154 Costs for Improved Accessories Level 2 (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$130	24	$124	$122	$119	$117	$116	$114	$112	$111	$109
IC	Low2	2018	$31	$31	$25	$25	$25	$25	$25	$25	$25
TC			$155	$153	$144	$142	$140	$139	$137	$136	$134

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.7.3 Secondary Axle Disconnect: Data and Assumptions for this Assessment

The 2017-2025 final rule estimated an effectiveness improvement of 1.0 to 1.5 percent for axle disconnect, which was refined to 1.2 to 1.4 percent based on the 2011 Ricardo report.

EPA has reviewed the cost and effectiveness figures used in the Draft TAR. There were no public comments received with supporting data that would provide basis for a change to the cost or effectiveness estimates for this technology, nor has EPA found additional information that supports such a change since the Draft TAR. EPA is retaining the Draft TAR figures for the Proposed Determination analysis. The cost associated with secondary axle disconnect is equivalent to that used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.155 Costs for Secondary Axle Disconnect (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$88	24	$84	$83	$81	$80	$78	$77	$76	$75	$74
IC	Low2	2018	$21	$21	$17	$17	$17	$17	$17	$17	$17
TC			$105	$104	$98	$97	$95	$94	$93	$92	$91

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.7.4 Low Drag Brakes: Data and Assumptions for this Assessment

The 2017-2025 final rule and Draft TAR estimated the effectiveness of low drag brakes to be to 0.8 percent. EPA continues to use this estimate for this Proposed Determination analysis based on the 2011 Ricardo study and the 2015 NAS report.

In comments on the Draft TAR, Toyota commented on several aspects of EPA's low-drag brake assessment. With respect to the Draft TAR analysis, Toyota commented on the conclusions regarding the Direct Manufacturing Costs (DMC) and stated that in order to "calculate such a detailed cost, it must be fixed with a special brake system of that of a specific supplier."

EPA notes that the DMC for this technology is not meant to represent a single supplier's cost, but rather an aggregate cost representing all of the changes that can be made to the brake system to reduce drag, including caliper seal and return rate and rotor and lining changes. For this Proposed Determination, the conclusions regarding DMC for low-drag brakes have been carried over from the 2012 FRM and from the Draft TAR.

Toyota also commented on EPA's summary of available zero drag brake systems. In response to these comments, updates have been made to the description of this technology in Chapter 2.2.8.4. Zero-drag brakes are not, however, part of this Proposed Determination analysis.

The cost associated with low drag brakes for the present analysis is equivalent to that used in the Draft TAR, updated to 2015 dollars. The costs are shown below.

Table 2.156 Costs for Low Drag Brakes (dollar values in 2015$)

Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
DMC	$64	1	$64	$64	$64	$64	$64	$64	$64	$64	$64
IC	Low2	2018	$15	$15	$12	$12	$12	$12	$12	$12	$12
TC			$79	$79	$76	$76	$76	$76	$76	$76	$76

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.8 Air Conditioning: Data and Assumptions for this Assessment

Air conditioning (A/C) system technologies include improved hoses, connectors and seals for leakage control. They also include improved compressors, expansion valves, heat exchangers and the control of these components for the purposes of improving tailpipe CO_2 emissions and fuel economy as a result of A/C use.

The Draft TAR generated extensive public comment relating to the A/C credit program, credit application procedures, the AC17 test procedure, testing requirements, and similar topics. Since these comments were concerned with off-cycle credit opportunities and details of the compliance process, and not with cost or effectiveness inputs to the Proposed Determination analysis, they are addressed in Chapter 2.2.9 (Air Conditioning Efficiency and Leakage Credits).

For this Proposed Determination analysis, EPA is continuing to use the cost and effectiveness estimates that were used in the Draft TAR analysis, updated to 2015 dollars. For more information on these estimates, see Section 5.1 of the 2012 TSD.

Table 2.157 Costs for A/C Controls (dollar values in 2015$)

Cost type	2017	2018	2019	2020	2021	2022	2023	2024	2025
TC	$94	$120	$138	$145	$158	$155	$148	$146	$143

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.9 Additional Off-cycle Credits and Costs

In past analyses, EPA has included technology costs and additional off-cycle credits for active aerodynamics (Aero2) and stop-start. While the off-cycle credits of these technologies were never considered when determining the feasibility of the standards, as air conditioning credits were, they have been considered to be relatively cost effective and expected to be widely used to comply. As a result, past analyses have shown considerable penetration of these technologies in our control case OMEGA runs.

Beyond off-cycle credits provided for active aero and stop-start, there are other technologies for which EPA provides off-cycle credits. Those technologies are included in what EPA calls the “off-cycle menu” and were codified in the 2012 FRM which specifies the level of credit available to those technologies without further demonstration. The off-cycle menu is shown in Table 2.158 and the program is described in more detail, along with a discussion of credits generated by manufacturers in MY2015, in TSD Chapter 2.2.10.

Table 2.158 Off-Cycle "Menu" Technologies and Credits for Cars & Light Trucks

Technology	gCO_2/mi Credit for Cars	gCO_2/mi Credit for Trucks
High efficiency exterior lights	1.0	1.0
Waster heat recovery	0.7	0.7
Solar panels for battery charging	3.3	3.3
Solar panels for active cabin ventilation & battery charging	2.5	2.5
Active aerodynamic improvements (Aero2)	0.6	1.0
Stop-start with heater circulation system	2.5	4.4
Stop-start without heater circulation system	1.5	2.9
Active transmission warm-up	1.5	3.2
Active engine warm-up	1.5	3.2
Solar/thermal control	up to 3.0	up to 4.3

Until now, we have not included the use of these menu off-cycle technologies in our OMEGA modeling since we did not have estimates of their costs. In comments on the Draft TAR, several auto industry commenters suggested that they plan to expand their use of off-cycle credits, including the menu technologies, in the coming years. These commenters even suggested that EPA remove the current 10 gram/mile cap on use of menu technologies, which seems an indication that manufacturers appear to be planning to maximize their use of these technologies throughout their fleets. In EPA's latest GHG Manufacturer Performance Report for MY2015, auto manufacturers used a fleet-wide average 3.0 gCO_2/mi of off-cycle menu credits. This makes clear that these credits are important to manufacturers and are, apparently, cost effective approaches to controlling GHGs.

For this Proposed Determination analysis, we are incorporating as technology options into OMEGA the use of additional off-cycle credit opportunities. Given that these credits are an available compliance option, EPA considers it reasonable to assess their potential use in considering the appropriateness (including feasibility and cost) of the 2022-2025MY standards. The approach being used in this Proposed Determination is not to focus on particular off-cycle technologies or their costs and credits, but rather to estimate the additional costs and credits based on the costs estimated by OMEGA. Specifically, we used the "single OEM" or "Perfect Trading" OMEGA run presented in the Draft TAR as a sensitivity (see Draft TAR Chapter 12.1.2). That run estimates the impacts of perfect trading amongst OEMs since the fleet is run as a single OEM. This is a "best case" or least-cost scenario. Using the results of that run, for the Control case in 2025, the costs associated with achieving the reference case targets of roughly 237 gCO_2/mi were $442, and the costs of the control case targets of roughly 199 gCO_2/mi were $1,307 (see Table 2.159). Note that both of these costs and the CO_2 values noted are OMEGA-core values and, as such, make no consideration of A/C credits, which is what we want for this exercise. Using the results of this "perfect trading" run further, we were able to generate the cost per gCO_2/mi value of $34 and applied a 30 percent premium resulting in a $45 (2013$) cost for each gram of CO2 reduced. This cost was applied to an "off-cycle technology level 1" credit of 1.5 gCO2/mi. For an off-cycle level 2 credit of 3 g/mi, we applied a 60 percent premium to the $34 value to arrive at a $55/gCO2/mi value (2013$) as shown in Table 2.160.

Table 2.159 Cost per gCO_2/mi within the Indicated Ranges for the Perfect Trading Sensitivity Run Presented in the Draft TAR (2013$)

Target CO_2	Delta CO_2	$/vehicle	Delta Cost	$/$gCO_2$/mi
237.2		$442		
230.0	7.15	$550	$108	$15
220.0	9.98	$726	$176	$18
210.0	9.98	$972	$246	$25
200.1	9.97	$1,277	$305	$31
199.2	0.9	$1,307	$31	$34

Table 2.1602 Basis for Off-cycle Credit Values and Costs used in OMEGA

Off-cycle "Technology"	Valued at (in 2013$)	Credit Value	DMC (in 2015$)
OC1	$45/$gCO_2$/mi	1.5 gCO_2/mi	$69
OC2	$55/$gCO_2$/mi	3.0 gCO_2/mi	$170

We have applied learning curve 29 to these costs and a low complexity markup to arrive at the costs shown in Table 2.161.

Table 2.161 Costs for Off-Cycle Technologies Level 1 & 2 (dollar values in 2015$)

Tech	Cost type	DMC: base year cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
OC1	DMC	$69	29	$69	$68	$66	$65	$64	$63	$62	$61	$60
OC2	DMC	$170	29	$170	$166	$162	$159	$156	$154	$151	$149	$147
OC1	IC	Low2	2024	$17	$17	$17	$17	$17	$17	$17	$17	$13
OC2	IC	Low2	2024	$41	$41	$41	$41	$41	$41	$41	$41	$33
OC1	TC			$86	$85	$83	$82	$81	$80	$79	$78	$73
OC2	TC			$211	$207	$203	$200	$197	$195	$192	$190	$180

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

2.3.4.10 Cost Tables for Individual Technologies Not Presented Above

Costs associated with SCR-equipped diesel vehicles are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs incremental to the baseline engine configuration for our different vehicle classes are shown below. These costs are used to characterize technology costs in the baseline fleet; EPA does not build OMEGA packages using this technology and instead uses the advanced diesel technology presented below.

Table 2.162 Costs for SCR-equipped Diesel Technology for Different Vehicle Classes (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	$2,531	23	$2,291	$2,255	$2,222	$2,191	$2,162	$2,135	$2,110	$2,086	$2,064

2	DMC	$2,531	23	$2,291	$2,255	$2,222	$2,191	$2,162	$2,135	$2,110	$2,086	$2,064
3	DMC	$3,112	23	$2,817	$2,773	$2,732	$2,694	$2,659	$2,626	$2,595	$2,565	$2,537
4	DMC	$3,112	23	$2,817	$2,773	$2,732	$2,694	$2,659	$2,626	$2,595	$2,565	$2,537
5	DMC	$3,112	23	$2,817	$2,773	$2,732	$2,694	$2,659	$2,626	$2,595	$2,565	$2,537
6	DMC	$3,568	23	$3,231	$3,180	$3,133	$3,090	$3,049	$3,011	$2,975	$2,941	$2,909
1	IC	Med2	2018	$969	$968	$724	$723	$722	$721	$720	$719	$719
2	IC	Med2	2018	$969	$968	$724	$723	$722	$721	$720	$719	$719
3	IC	Med2	2018	$1,192	$1,190	$890	$888	$887	$886	$885	$884	$884
4	IC	Med2	2018	$1,192	$1,190	$890	$888	$887	$886	$885	$884	$884
5	IC	Med2	2018	$1,192	$1,190	$890	$888	$887	$886	$885	$884	$884
6	IC	Med2	2018	$1,367	$1,364	$1,020	$1,019	$1,018	$1,016	$1,015	$1,014	$1,013
1	TC			$3,261	$3,223	$2,946	$2,914	$2,884	$2,856	$2,830	$2,805	$2,782
2	TC			$3,261	$3,223	$2,946	$2,914	$2,884	$2,856	$2,830	$2,805	$2,782
3	TC			$4,009	$3,963	$3,622	$3,583	$3,546	$3,512	$3,480	$3,450	$3,421
4	TC			$4,009	$3,963	$3,622	$3,583	$3,546	$3,512	$3,480	$3,450	$3,421
5	TC			$4,009	$3,963	$3,622	$3,583	$3,546	$3,512	$3,480	$3,450	$3,421
6	TC			$4,597	$4,544	$4,153	$4,108	$4,066	$4,027	$3,990	$3,956	$3,923

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with advanced diesel vehicles (i.e., Tier 3 compliant) are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs incremental to the baseline engine configuration for our different vehicle classes are shown below. These costs are used when building OMEGA diesel packages.

Table 2.163 Costs for Advanced Diesel Technology for Different Vehicle Classes (dollar values in 2015$)

Curb Weight Class	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	$2,581	23	$2,337	$2,300	$2,266	$2,235	$2,205	$2,178	$2,152	$2,127	$2,104
2	DMC	$2,581	23	$2,337	$2,300	$2,266	$2,235	$2,205	$2,178	$2,152	$2,127	$2,104
3	DMC	$3,162	23	$2,863	$2,818	$2,776	$2,738	$2,702	$2,668	$2,636	$2,606	$2,578
4	DMC	$3,162	23	$2,863	$2,818	$2,776	$2,738	$2,702	$2,668	$2,636	$2,606	$2,578
5	DMC	$3,162	23	$2,863	$2,818	$2,776	$2,738	$2,702	$2,668	$2,636	$2,606	$2,578
6	DMC	$3,618	23	$3,276	$3,225	$3,177	$3,133	$3,092	$3,053	$3,017	$2,983	$2,950
1	IC	Med2	2018	$988	$987	$738	$737	$736	$735	$734	$734	$733
2	IC	Med2	2018	$988	$987	$738	$737	$736	$735	$734	$734	$733
3	IC	Med2	2018	$1,211	$1,209	$904	$903	$902	$901	$900	$899	$898
4	IC	Med2	2018	$1,211	$1,209	$904	$903	$902	$901	$900	$899	$898
5	IC	Med2	2018	$1,211	$1,209	$904	$903	$902	$901	$900	$899	$898
6	IC	Med2	2018	$1,386	$1,384	$1,034	$1,033	$1,032	$1,031	$1,029	$1,028	$1,027
1	TC			$3,325	$3,287	$3,004	$2,971	$2,941	$2,913	$2,886	$2,861	$2,837
2	TC			$3,325	$3,287	$3,004	$2,971	$2,941	$2,913	$2,886	$2,861	$2,837
3	TC			$4,074	$4,027	$3,680	$3,640	$3,603	$3,568	$3,536	$3,505	$3,476
4	TC			$4,074	$4,027	$3,680	$3,640	$3,603	$3,568	$3,536	$3,505	$3,476
5	TC			$4,074	$4,027	$3,680	$3,640	$3,603	$3,568	$3,536	$3,505	$3,476
6	TC			$4,662	$4,608	$4,211	$4,166	$4,123	$4,084	$4,046	$4,011	$3,978

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

Costs associated with powersplit HEVs are equivalent to those used in the Draft TAR, updated to 2015 dollars. The costs incremental to the baseline configuration for our different vehicle classes are shown below. These costs are used to characterize technology costs in the baseline fleet; EPA does not build OMEGA packages using this technology and instead uses the strong HEV technology presented earlier.

Table 2.164 Costs for Powersplit HEV Technology for Different Vehicle Classes (dollar values in 2015$)

Tech	Cost type	DMC: base cost IC: complexity	DMC: learning curve IC: near term thru	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	DMC	$3,224	24	$3,083	$3,023	$2,969	$2,919	$2,873	$2,831	$2,792	$2,755	$2,720
2	DMC	$3,588	24	$3,431	$3,365	$3,304	$3,249	$3,198	$3,151	$3,107	$3,066	$3,028
3	DMC	$3,882	24	$3,712	$3,640	$3,575	$3,515	$3,460	$3,409	$3,361	$3,317	$3,276
4	DMC	$4,710	24	$4,504	$4,417	$4,337	$4,265	$4,198	$4,136	$4,078	$4,025	$3,974
5	DMC	$5,792	24	$5,539	$5,431	$5,333	$5,244	$5,162	$5,085	$5,015	$4,949	$4,887
6	DMC	$5,792	24	$5,539	$5,431	$5,333	$5,244	$5,162	$5,085	$5,015	$4,949	$4,887
1	IC	High1	2018	$1,808	$1,804	$1,105	$1,104	$1,102	$1,101	$1,100	$1,099	$1,098
2	IC	High1	2018	$2,012	$2,008	$1,230	$1,229	$1,227	$1,225	$1,224	$1,223	$1,222
3	IC	High1	2018	$2,177	$2,172	$1,331	$1,329	$1,327	$1,326	$1,324	$1,323	$1,321
4	IC	High1	2018	$2,641	$2,636	$1,615	$1,613	$1,610	$1,609	$1,607	$1,605	$1,603
5	IC	High1	2018	$3,248	$3,241	$1,986	$1,983	$1,980	$1,978	$1,976	$1,974	$1,972
6	IC	High1	2018	$3,248	$3,241	$1,986	$1,983	$1,980	$1,978	$1,976	$1,974	$1,972
1	TC			$4,891	$4,827	$4,074	$4,023	$3,976	$3,932	$3,891	$3,854	$3,818
2	TC			$5,444	$5,373	$4,535	$4,477	$4,425	$4,376	$4,331	$4,289	$4,249
3	TC			$5,889	$5,812	$4,906	$4,844	$4,787	$4,734	$4,685	$4,640	$4,597
4	TC			$7,145	$7,052	$5,952	$5,877	$5,808	$5,744	$5,685	$5,630	$5,578
5	TC			$8,786	$8,672	$7,319	$7,227	$7,142	$7,063	$6,990	$6,922	$6,859
6	TC			$8,786	$8,672	$7,319	$7,227	$7,142	$7,063	$6,990	$6,922	$6,859

Note: DMC=direct manufacturing costs; IC=indirect costs; TC=total costs.

References

[1] U.S. EPA, October 2014, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014*, Report EPA-420-R -14-023a.

[2] Stanton, D.W. "Light Duty Efficient, Clean Combustion." Final Report by Cummins, Inc., to the U.S. Department of Energy, Report No. DE-FC26-07NT43279, June 3, 2011. http://www.osti.gov/scitech/servlets/purl/1038535/.

[3] Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, doi:10.4271/2016-01-1007.

[4] EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015," EPA-420-R-15-016, December 2015.

[5] Yu, C., Park, K., Han, S., and Kim, W., "Development of Theta II 2.4L GDI Engine for High Power & Low Emission," SAE Technical Paper 2009-01-1486, 2009, doi: 10.4271/2009-01-1486.

[6] Saeki, T., Tsuchiya, T, Iwahashi, K., Abe, S. "Development of V6 3.5-Liter 2GR-FSE Engine." Toyota Technical Review, Volume 55, No. 1, pp 94-99, November 2006. Link?

[7] Ikoma, T., Abe, S., Sonoda, Y., Suzuki, H. et al., "Development of V-6 3.5-liter Engine Adopting New Direct Injection System," SAE Technical Paper 2006-01-1259, 2006, doi: 10.4271/2006-01-1259.

[8] Yamaguchi, J. "Lexus Gives V6 Dual Injection." SAE Automotive Engineering International, January 2006, pp 17-20.

[9] U.S. EPA. "Annual Certification Test Results & Data." Light Duty Vehicle Data - Certified Vehicle Test Result Report Data, MY2010-2016. https://www.epa.gov/compliance-and-fuel-economy-data/annual-certification-test-data-vehicles-and-engines.

[10] Ford Motor Company. 2016. "More Torque and Better Boost: 2017 Ford F-150 to Debut with All-New 3.5-Liter Ecoboost Engine and 10-Speed Transmission." https://media.ford.com/content/fordmedia/fna/us/en/news/2016/05/03/2017-ford-f150-more-torque-better-boost.pdf, last accessed July 5, 2016.

[11] Ford Motor Company. 2015. "Ford Marks Production Milestone As 5-Millionth EcoBoost-Equipped Vehicle Rolls Off Assembly Line." https://media.ford.com/content/fordmedia/fna/us/en/news/2015/03/17/ford-marks-production-milestone-as-5-millionth-ecoboost-equipped.pdf, last accessed July 5, 2016.
[12] Volkswagen. 2015. http://www.volkswagen.co.uk/technology/petrol/active-cylinder-technology-act, last accessed July 5, 2016.
[13] Eichler, F., Demmelbauer-Ebner, W., Theobald, J., Stiebels, B., Hoffmeyer, H., Kreft, M. "The New EA211 TSI® evo from Volkswagen." 37. Internationales Wiener Motorensymposium 2016.
[14] Schamel, A., Scheidt, M., Weber, C. Faust, H. Is Cylinder Deactivation a Viable Option for a Downsized 3-Cylinder Engine? Vienna Motor Symposium, 2015.
[15] Wilcutts, M., Switkes, J., Shost, M. and Tripathi, A., "Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines," SAE Int. J. Engines 6(1):2013, doi: 10.4271/2013-01-0359.
[16] Ernst, R., Fridfeldt, R., Lamb, S., Lloyd-Thomas, D., Phlips, P., Russell, R., Zenner, T. "The New 3 Cylinder 1.0L Gasoline Direct Injection Turbo Engine from Ford. 20th Aachen Colloquium - Automobile and Engine Technology, 2011.
[17] Wada, Y., Nakano, K., Mochizuki, K., and Hata, R., "Development of a New 1.5L I4 Turbocharged Gasoline Direct Injection Engine," SAE Technical Paper 2016-01-1020, 2016, doi: 10.4271/2016-01-1020.
[18] Nakano, K., Wada, Y., Jono, M., Narihiro, S. "New In-Line 4-Cylinder Gasoline Direct Injection Turbocharged Downsizing Engine." Honda R&D Technical Review, April 2016, pp 139-146.
[19] National Instruments. Subsystems Required to Control Low Temperature Combustion Engines. Jun 11, 2014. http://www.ni.com/white-paper/13516/en/pdf, last accessed August 25, 2015.
[20] Takahashi, D., Nakata, K., Yoshihara, Y., Ohta, Y. et al., "Combustion Development to Achieve Engine Thermal Efficiency of 40% for Hybrid Vehicles," SAE Technical Paper 2015-01-1254, 2015, doi: 10.4271/2015-01-1254.
[21] Yamada, T., Adachi, S., Nakata, K., Kurauchi, T. et al. "Economy with Superior Thermal Efficient Combustion (ESTEC)," SAE Technical Paper 2014-01-1192 doi: 10.4271/2014-01-1192.
[22] Lee, S., Schenk, C., and McDonald, J., "Air Flow Optimization and Calibration in High-Compression-Ratio Naturally Aspirated SI Engines with Cooled-EGR," SAE Technical Paper 2016-01-0565, 2016, doi: 10.4271/2016-01-0565.
[23] Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 M 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, doi: 10.4271/2016-01-1007.
[24] Souhaite, P., Mokhtari, S. "Combustion system design of the new PSA Peugeot Citroën EB TURBO PURE TECH engine," Proceedings: Internationaler Motorenkongress 2014, DOI: 10.1007/978-3-658-05016-0_5.
[25] Budack, R., Kuhn, M., Wurms, R., Heiduk, T., "Optimization of the Combustion Process as Demonstrated on the New Audi 2.0l TFSI," 24th Aachen Colloquium Automobile and Engine Technology 2015.
[26] Wurms, R., Budack, R., Grigo, M., Mendl, G., Heiduk, T., Knirsch, S. "The new Audi 2.0l Engine with innovative Rightsizing," 36. Internationales Wiener Motorensymposium 2015.
[27] Hirose, I. "Mazda 2.5L SKYACTIV-G Engine with New Boosting Technology." 37. Internationales Wiener Motorensymposium 2016.
[28] Hatano, J., Fukushima, H., Sasaki, Y., Nishimori, K., Tabuchi, T., Ishihara, Y. "The New 1.6L 2-Stage Turbo Diesel Engine for HONDA CR-V." 24th Aachen Colloquium - Automobile and Engine Technology 2015.
[29] Steinparzer, F., Nefischer, P., Hiemesch, D., Kaufmann, M., Steinmayr, T. "The New Six-Cylinder Diesel Engines from the BMW In-Line Engine Module." 24th Aachen Colloquium - Automobile and Engine Technology 2015.
[30] Eder, T., Weller, R., Spengel, C., Böhm,J., Herwig, H., Sass, H. Tiessen, J., Knauel, P. "Launch of the New Engine Family at Mercedes-Benz." 24th Aachen Colloquium - Automobile and Engine Technology 2015.
[31] Koeberlein, D. "Cummins SuperTruck Program - Technology and System Level Demonstration of Highly Efficient and Clean, Diesel Powered Class 8 Trucks." U.S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, June 9-12, 2015.
[32] Gibble, J. "Volvo SuperTruck - Powertrain Technologies for Efficiency Improvement." U.S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, June 9-12, 2015.
[33] Lückert, P., Arndt, S., Duvinage, F., Kemmner, M., Binz, R., Storz, O., Reusch, M., Braun, T., Ellwanger, S. "The New Mercedes-Benz 4-Cylinder Diesel Engine OM654 – The Innovative Base Engine of the New Diesel Generation." 24th Aachen Colloquium - Automobile and Engine Technology 2015.
[34] Busch, R., Jennes, J., Müller, J., Krüger, M., Naber, D., Kauss, H. "Emission and Fuel Consumption Optimized Turbo Charging of Passenger Car Diesel Engines." Vienna Motor Symposium, 2015.
[35] Ruth, M. "ATP-LD; Cummins Next Generation Tier 2 Bin 2 Diesel Engine." .S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, May 14-17, 2013.

[36] Ruth, M. "ATP-LD; Cummins Next Generation Tier 2 Bin 2 Diesel Engine." .S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, June 9-12, 2015.
[37] U.S. DOE, April 8, 2015. Cummins Improving Pick-Up Truck Engine Efficiency with DOE and Nissan. Accessed on 2/3/2016 at the following URL: http://energy.gov/eere/success-stories/articles/cummins-improving-pick-truck-engine-efficiency-doe-and-nissan.
[38] Ogihara, H., "Research Into Surface Improvement for Low Friction Pistons," SAE Technical Paper 2005-01-1647, 2005, doi: 10.4271/2005-01-1647.
[39] Kim, Y., Kim, S.J., Lee, J., Lim, D. "Nanodiamond Reinforced PTFE Composite Coatings." *MTZ* 76 (2) pp 32-35, February 2015.
[40] Hanke, W., Ando, H., Fahr, M., Voigt, M. "Friction Reduction in Power Cylinder Systems for Passenger Car Diesel Engines" MTZ 75 (2) pp 26-31, February 2014.
[41] Landerl, C., Ruelicke, M., Durst, B., Mattes, W. "The New BMW Inline 6-Cylinder Gasoline Engine with TwinPower Turbo, Direct Injection, and VALVETRONIC in the New BMW 7 Series." 24th Aachen Colloquium - Automobile and Engine Technology 2015.
[42] Neußer, H.K. "The Car of the Future will continue to Fascinate People." Oral Presentation, Vienna Motor Symposium, 2015.
[43] Ragot, P. and Rebbert, M., "Investigations of Crank Offset and Its Influence on Piston and Piston Ring Friction Behavior Based on Simulation and Testing," SAE Technical Paper 2007-01-1248, 2007, doi: 10.4271/2007-01-1248.
[44] Toyota Motor Corporation. 2009 Toyota Prius Service Manual. Toyota Technical Information System. https://techinfo.toyota.com/.
[45] Confer, K., Kirwan, J., and Engineer, N., "Development and Vehicle Demonstration of a Systems-Level Approach to Fuel Economy Improvement Technologies," SAE Technical Paper 2013-01-0280, 2013, doi: 10.4271/2013-01-0280.
[46] U.S. EPA, October 2014, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014*, Report EPA-420-R -14-023a, p. 74.
[47] "Once-promising dual-clutch transmissions lose favor in U.S.," *Automotive News*, December 7, 2015 http://www.autonews.com/article/20151207/OEM06/312079988/once-promising-dual-clutch-transmissions-lose-favor-in-u.s.
[48] Newman, K., Kargul, J., and Barba, D., "Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA," SAE Technical Paper 2015-01-1140, 2015, doi: 10.4271/2015-01-1140.
[49] Newman, K., Kargul, J., and Barba, D., "Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation," *SAE Int. J. Engines* 8(3):1417-1427, 2015, doi: 10.4271/2015-01-1142.
[50] Moskalik, Andrew, Barba, Dan, and Kargul, John, "Investigating the Effect of Advanced Automatic Transmissions on Fuel Consumption Using Vehicle Testing and Modeling," to be presented at the 2016 SAE International Congress, April 2016.
[51] Gall, J., "2011 Dodge Charger V6," http://www.caranddriver.com/reviews/2011-dodge-charger-v6-test-review, (July 2011), accessed July 2016.
[52] Gall, J., "2012 Dodge Charger SXT V6," http://www.caranddriver.com/reviews/2012-dodge-charger-sxt-v6-test-review (January 2012), accessed July 2016.
[53] Dick, A., Greiner, J., Locher, A., and Jauch, F., "Optimization Potential for a State of the Art 8-Speed AT," *SAE International Journal of Passenger Cars – Mechanical Systems,* 6(2):899-907, 2013, doi: 10.4271/2013-01-1272.
[54] Aoki, T., Kato, H., Kato, N., and Masaru, M., "The World's First Transverse 8-Speed Automatic Transmission," SAE Technical Paper 2013-01-1274, 2013, doi: 10.4271/2013-01-1274.
[55] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC," presented at the 2014 Car Training Institute Transmission Symposium, Rochester MI.
[56] Gaertner, L. and Ebenhoch, M., "The ZF Automatic Transmission 9HP48 Transmission System, Design and Mechanical Parts," *SAE International Journal of Passenger Cars – Mechanical Systems,* 6(2):908-917, 2013, doi: 10.4271/2013-01-1276.
[57] Shidore, N. et. al. 2014. "Impact of Advanced Technologies on Engine Targets." Project VSS128, DOE Merit Review, June.
[58] Eckl, B., and D. Lexa. 2012. How Many Gears do the Markets Need? GETRAG. International CTI Symposium, Berlin, Germany, December.
[59] Darrell Robinette, 2014, "A DFSS Approach to Determine Automatic Transmission Gearing Content for Powertrain-Vehicle System Integration, *SAE International Journal of Passenger Cars – Mechanical Systems* 7 (3).

[60] Juergen Greiner, Martin Grumbach, Albert Dick, and Cristophe Sasse, 2015, "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE technical paper 2015-01-1087
[61] NAS, 2011, p. 62 footnote.
[62] NAS (2015), Prepublication Copy, p. 5-16.
[63]Wikimedia Commons. https://commons.wikimedia.org/wiki/File:ZF_Stufenautomatgetriebe_8HP70.jpg Photo credit: Stefan Krause.
[64] U.S. EPA, October 2014, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014*, Report EPA-420-R -14-023a, p. 75.
[65] Start of Volume Production: New Generation of the ZF 8-Speed "Automatic Transmission in the BMW 5 Series," August 21, 2014, https://www.zf.com/corporate/en_de/magazine/magazin_artikel_viewpage_22067944.html.
[66] Jens Meiners, "2016 Mini Cooper Clubman Revealed: Another Bigger, Four-Door Mini," *Car and Driver*, June 2015, http://www.caranddriver.com/news/2016-mini-clubman-revealed-news.
[67] Gaertner, L. and Ebenhoch, M., "The ZF Automatic Transmission 9HP48 Transmission System, Design and Mechanical Parts," SAE Int. J. Passeng. Cars - Mech. Syst. 6(2):908-917, 2013, doi: 10.4271/2013-01-1276.
[68] "Land Rover To Demonstrate Latest Technical Innovation With The World's First 9-Speed Automatic Transmission," Land Rover Media Centre, February 27, 2013, http://newsroom.jaguarlandrover.com/en-in/land-rover/news/2013/02/rr_rre_9-speed_transmission_270213/.
[69] Daimler. 2013. New Nine-Speed Automatic Transmission Debuts in the Mercedes-Benz E350 Blue Tec: Premier of the new 9G-Tronic. Daimler, July 24. http://media.daimler.com/dcmedia/0-921-1553299-1-1618134-1-0-1-0-0-0-0-1549054-0-1-0-0-0-0-0.html.
[70] Motor Authority: Technology Preview: We Drive Honda's 10-Speed Automatic Transmission, http://www.motorauthority.com/news/1100878_technology-preview-we-drive-hondas-10-speed-automatic-transmission.
[71] ZF, "Fuel Saving and Minimizing CO_2 Emissions: 6% Lower Fuel Consumption," http://www.zf.com/corporate/en_de/products/innovations/8hp_automatic_transmissions/lower_consumption/lower_consumption.html.
[72] Dick, A., Greiner, J., Locher, A., and Jauch, F., "Optimization Potential for a State of the Art 8-Speed AT," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):899-907, 2013, doi: 10.4271/2013-01-1272.
[73] The New Generation of 8-Speed Automatic Transmission, ZF http://www.zf.com/corporate/en_de/products/innovations/8hp_automatic_transmissions/8hp_automatic_transmission.html.
[74] Greiner, J., Grumbach, M., Dick, A., and Sasse, C., "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE Technical Paper 2015-01-1087, 2015, doi: 10.4271/2015-01-1087.
[75] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC from Mercedes- Benz," presented at the 2014 CTI Symposium, Plymouth, MI.
[76] Greiner, J. and Grumbach, M., "Automatic Transmission Systems Beyond 2020 - Challenges and Competition," SAE Technical Paper 2013-01-1273, 2013, doi: 10.4271/2013-01-1273.
[77] Driveline News, Jan 22 2014, "BMW and Mini Strategy Revealed," http://www.drivelinenews.com/transmission-insight/bmw-and-mini-transmission-strategy-revealed/.
[78] Markus Nell, "BMW's flexible powertrain family with a new generation of transverse automatic transmissions," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[79] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[80] Darrell Robinette and Daniel Wehrwein, "Automatic Transmission Technology Selection Using Energy Analysis" presented at the CTI Symposium 9th International 2015 Automotive Transmissions, HEV and EV Drives.
[81] Juergen Greiner, Martin Grumbach, Albert Dick, and Cristophe Sasse, 2015, "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE technical paper 2015-01-1087.
[82] Darrell Robinette, 2014, "A DFSS Approach to Determine Automatic Transmission Gearing Content for Powertrain-Vehicle System Integration, SAE International Journal of Passenger Cars – Mechanical Systems 7 (3).
[83] Hans Greimel, "ZF CEO: We're not chasing 10-speeds," *Automotive News*, November 23, 2014, http://www.autonews.com/article/20141123/OEM10/311249990/zf-ceo:-were-not-chasing-10-speeds.
[84] NAS (2015), Prepublication Copy, p. 5-9.
[85]Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Dual-clutch_transmission.svg, Credit: Xavax.
[86] Carney, D. 2014. Honda's new 8-speed DCT uses a Torque Converter. *SAE Automotive Engineering Magazine*, August 6.
[87] NAS (2015), Prepublication Copy, p. 5-7.

[88] NRC (2015), Prepublication Copy, p. 5-7.
[89] Eckl, B., " DCT in the American Market: Transferring Customer Perceptions into Product Refinements," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[90] Eckl, B., and D. Lexa. 2012. How Many Gears do the Markets Need? GETRAG. International Car Training Institute Transmission Symposium, Berlin, Germany, December.
[91]Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Toyota_Super_CVT-i_01.JPG, Photo credit: Hatsukari715.
[92]Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Pivgetriebe.png, Credit: Büdeler Naumann
[93] Shinji Morihiro, "Fuel Economy Improvement by Transmission" presented at the CTI Symposium 8th International 2014 Automotive Transmissions, HEV and EV Drives.
[94] Masayoshi Nakasaki and Yoshikazu Oota, "Key Technologies Supporting Belt-type CVT Evolution," presented at the 2014 Car Training Institute Transmission Symposium, Rochester MI.
[95] Maruyama, F., Kojima, M., and Kanda, T., "Development of New CVT for Compact Car," SAE Technical Paper 2015-01-1091, 2015, doi: 10.4271/2015-01-1091.
[96] Hakamagi, J., Kono, T., Habuchi, R., Nishimura, N. et al., "Development of New Continuously Variable Transmission for 2.0-Liter Class Vehicles," SAE Technical Paper 2015-01-1101, 2015, doi: 10.4271/2015-01-1101.
[97] Shimokawa, Y., "Technology Development to Improve JATCO CVT8 Efficiency," SAE Technical Paper 2013-01-0364, 2013, doi: 10.4271/2013-01-0364.
[98] Lindsay Brooke, "JATCO's next-gen CVTs bring high ratio spreads, more efficiency," *Automotive Engineering Magazine*, April 23, 2012, http://articles.sae.org/10947/.
[99] Naotoshi, P. "Development of a New Generation CVT with Auxiliary Gear Box," SAE Technical Paper 2016-01-1109, 2016, doi: 10.4271/2016-01-1109.
[100] Naotoshi, P. "Development of a New Generation CVT with Auxiliary Gear Box," SAE Technical Paper 2016-01-1109, 2016, doi: 10.4271/2016-01-1109.
[101] Shimokawa, Y., "Technology Development to Improve JATCO CVT8 Efficiency," SAE Technical Paper 2013-01-0364, 2013, doi: 10.4271/2013-01-0364.
[102] Maruyama, F., Kojima, M., and Kanda, T., "Development of New CVT for Compact Car," SAE Technical Paper 2015-01-1091, 2015, doi: 10.4271/2015-01-1091.
[103] Inukai, K., Shibahara, A., Uchino, T., Keiichi, N. et al., "Development of High-Efficiency New CVT for Midsize Vehicle," SAE Technical Paper 2013-01-0365, 2013, doi: 10.4271/2013-01-0365.
[104] Hakamagi, J., Kono, T., Habuchi, R., Nishimura, N. et al., "Development of New Continuously Variable Transmission for 2.0-Liter Class Vehicles," SAE Technical Paper 2015-01-1101, 2015, doi: 10.4271/2015-01-1101.
[105] Don Sherman, Dec 2013, "The Unsinkable CVT: How the "Gearless" Transmission Is Getting Its Groove Back," *Car and Driver*, http://www.caranddriver.com/features/how-cvt-transmissions-are-getting-their-groove-back-feature.
[106] Shimokawa, Y., "Technology Development to Improve JATCO CVT8 Efficiency," SAE Technical Paper 2013-01-0364, 2013, doi: 10.4271/2013-01-0364.
[107] Maruyama, F., Kojima, M., and Kanda, T., "Development of New CVT for Compact Car," SAE Technical Paper 2015-01-1091, 2015, doi: 10.4271/2015-01-1091.
[108] Inukai, K., Shibahara, A., Uchino, T., Keiichi, N. et al., "Development of High-Efficiency New CVT for Midsize Vehicle," SAE Technical Paper 2013-01-0365, 2013, doi: 10.4271/2013-01-0365.
[109] Hakamagi, J., Kono, T., Habuchi, R., Nishimura, N. et al., "Development of New Continuously Variable Transmission for 2.0-Liter Class Vehicles," SAE Technical Paper 2015-01-1101, 2015, doi: 10.4271/2015-01-1101.
[110] Mamiko Inoue, "Advanced CVT control to achieve both fuel economy and drivability," presented at the 2015 Car Training Institute Transmission Symposium, Novi, MI.
[111] Masayoshi Nakasaki and Yoshikazu Oota, "Key Technologies Supporting Belt-type CVT Evolution," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[112] Dana Holding Corp. 2014. Dana Advances Development of VariGlide™ Continuously Variable Planetary Technology. PR Newswire, May 19. http://www.prnewswire.com/news-releases/dana-advances-development-of-variglide-continuously-variable-planetary-technology-259791981.html.
[113] Dick, A., J. Greiner, A. Locher, and F. Jauch. 2013. Optimization Potential for a State of the Art 8-Speed AT. SAE 2013-01-1272.
[114] Dick, A., Greiner, J., Locher, A., and Jauch, F., "Optimization Potential for a State of the Art 8-Speed AT," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):899-907, 2013, doi: 10.4271/2013-01-1272.
[115] Aoki, T., Kato, H., Kato, N., and Masaru, M., "The World's First Transverse 8-Speed Automatic Transmission," SAE Technical Paper 2013-01-1274, 2013, doi: 10.4271/2013-01-1274.

[116] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[117] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[118] Martin, K. 2012. Transmission Efficiency Developments. SAE Transmission and Driveline Symposium: Competition for the Future, October 17-18. Detroit, Michigan. [as cited in NAS (2015), Prepublication Copy, p. 5-22.].
[119] NSK Europe. 2014. New Low-Friction TM-Seal for Automotive Transmissions, http://www.nskeurope.com/transmission-bearings-low-friction-tm-seal-2373.htm.
[120] Christoph Dörr, "The New Automatic Transmission 9G-TRONIC," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[121] Noles, J. 2013. Development of Transmission Fluids Delivering Improved Fuel Efficiency by Mapping Transmission Response to Viscosity and Additive Changes. Presentation at the SAE Transmission & Driveline Symposium, Troy, Michigan, October 16-17.[as cited in NAS (2015), Prepublication Copy, p. 5-25.].
[122] NAS (2015), Prepublication Copy, p. 5-28.
[123] NAS (2015), Prepublication Copy, p. 5-27.
[124] Shimokawa, Y., "Technology Development to Improve JATCO CVT8 Efficiency," SAE Technical Paper 2013-01-0364, 2013, doi: 10.4271/2013-01-0364.
[125] Ando, T., Yagasaki, T., Ichijo, S., Sakagami, K. et al., "Improvement of Transmission Efficiency in CVT Shifting Mechanism Using Metal Pushing V-Belt," *SAE Int. J. Engines* 8(3):1391-1397, 2015, doi: 10.4271/2015-01-1103.
[126] Greiner, J., Grumbach, M., Dick, A., and Sasse, C., "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE Technical Paper 2015-01-1087, 2015, doi: 10.4271/2015-01-1087.
[127] Markus Nell, "BMW's flexible powertrain family with a new generation of transverse automatic transmissions," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[128] Markus Nell, "BMW's flexible powertrain family with a new generation of transverse automatic transmissions," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI.
[129] Albert Dick, Juergen Greiner, Anton Locher, and Friedemann Jauch, "Optimization Potential for a State of the Ary 8-Speed AT," *SAE International Journal of Passenger Cars - Mechanical Systems* 6(2):2013, doi: 10.4271/2013-01-1272.
[130] Darrell Robinette and Daniel Wehrwein, "Utilizing Energy Analysis Methods to Select Transmission Technologies and Optimize Powertrain-Vehicle System Fuel Consumption," presented at the SAE 2014 Transmission and Driveline Symposium.
[131] Markus Nell, "BMW's flexible powertrain family with a new generation of transverse automatic transmissions," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI
[132] Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Bauma_2007_ZF_Drehmomentwandler.jpg, Photo credit: Aconcagua.
[133] Weissler, Paul. 2011. "2012 Mazda3 Skyactiv achieves 40 mpg without stop/start." *Automotive Engineering Magazine*, October 28.
[134] Markus Nell, "BMW's flexible powertrain family with a new generation of transverse automatic transmissions," presented at the 2014 Car Training Institute Transmission Symposium, Rochester, MI
[135] Nelson, P. et al., "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric Drive Vehicles," Second Edition, Argonne National Laboratory, ANL-12/55 (December 2012).
[136] See EPA Docket EPA-HQ-OAR-2015-0827, Microsoft Excel attachment to Docket Item titled "Data and Charts for Selected Figures in Electrification Chapters of Proposed Determination TSD."
[137] See Table ES-3, "Selected Technology Penetrations to Meet MY2025 Standards," Draft TAR p. ES-10.
[138] Howell, D., "Electric Drive Vehicle Battery Status and Trends," Vehicle Technologies Office, Department of Energy. Presented at SAE Government-Industry Meeting, Washington, D.C., January 21, 2016.
[139] HybridCars.com, "September 2016 Dashboard." Retrieved on Nov. 2, 2016 from http://www.hybridcars.com/september-2016-dashboard/.
[140] Volkswagen AG, "The Future of the Volkswagen Group: Together Strategy 2025", retrieved on Nov. 3, 2016 from http://www.volkswagenag.com/content/vwcorp/info_center/en/talks_and_presentations/2016/06/together.bin.html/binarystorageitem/file/Presse_englisch_NICHTanimiert_Version_24.pdf.
[141] Boston, W., "Volkswagen to Boost Electric Vehicles, Pursue Self-Driving Cars," The Wall Street Journal, June 15, 2016.

---

142 Daimler, "Daimler invests massively in green powertrain technologies: All Mercedes-Benz model series will be electrified," Press Release, June 14, 2016. Retrieved from http://media.daimler.com/marsMediaSite/ko/en/11108480.
143 BMW, "New generation of plug-in hybrid models," Press Release, December 1, 2014. Retrieved from https://www.press.bmwgroup.com/global/article/detail/T0197302EN/new-generation-of-plug-in-hybrid-models.
144 Eisenstein, P., "Volvo Is Pushing Down the Pedal on Battery-Powered Cars," NBCNews.com, June 14, 2016. Retrieved from http://www.nbcnews.com/business/autos/volvo-pushing-down-pedal-battery-powered-cars-n591336.
145 Ford Motor Co., "Ford Investing $4.5 Billion in Electrified Vehicle Solutions, Reimagining How to Create Future Vehicle User Experiences," Press Release, December 10, 2015. Retrieved on November 3, 2016 from https://media.ford.com/content/fordmedia/fna/us/en/news/2015/12/10/fordinvesting45billioninelectrifiedvehiclesolutions.html.
146 Nikkei Asian Review, "Toyota to mass produce electric vehicles," November 7, 2016. Retrieved on November 7, 2016 from http://asia.nikkei.com/Japan-Update/Toyota-to-mass-produce-electric-vehicles
147 Tajitsu, N. et al., "Toyota, in about-face, may mass-produce long-range electric cars: Nikkei," November 7, 2016. Retrieved on November 7, 2016 from http://www.reuters.com/article/us-toyota-electric-cars-idUSKBN13204D.
148 See Table ES-3, "Selected Technology Penetrations to Meet MY2025 Standards," Draft TAR p. ES-10.
149 See Table 3.5-25 of RIA, 2017-2025 FRM.
150 "Obama Administration Announces New Actions To Accelerate The Deployment of Electrical Vehicles and Charging Infrastructure," Press Release, The White House, November 3, 2016.
151 Partial Consent Decree, in re: Volkswagen "Clean Diesel" Marketing, Sales Practices, and Products Liability Litigation, Case 3:15-md-02672-CRB Document 1605-1 Filed 06/28/16. Retrieved on November 7, 2016 from https://www.epa.gov/sites/production/files/2016-06/documents/vwpartialsettlement-cd.pdf
152 "Fixing America's Surface Transportation Act—Designation of Alternative Fuel Corridors," Federal Register, Vol. 81, No. 141, Friday, July 22, 2016. See also: http://www.fhwa.dot.gov/environment/alternative_fuel_corridors/.
153 Nykvist, B. and Nilsson, M.; "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature Climate Change, March 2015; doi: 10.1038/NCLIMATE2564.
154 Green Car Congress, "GM and LG expand their relationship on Bolt EV; 12 components, including PEEM," October 20, 2015. Retrieved from http://www.greencarcongress.com/2015/10/20151020-gmlg.html.
155 Siemens, "Siemens and Valeo join forces for global leadership in powertrains for electric cars," Press Release, April 18, 2016. Retrieved April 29, 2016 from http://www.siemens.com/press/PR2016040250COEN.
156 Schultz, Jay W. and Huard, Steve, "Comparing AC Induction with Permanent Magnet motors in hybrid vehicles and the impact on the value proposition." White Paper, Parker Hannifin, 2013. Retrieved from http://www.parkermotion.com/whitepages/Comparing_AC_and_PM_motors.pdf on Oct 14, 2015.
157 Widmer, James D. et al., "Electric vehicle traction motors without rare earth magnets," Sustainable Materials and Technologies 3 (2015) 7–13. doi:10.1016/j.susmat.2015.02.001 .
158 Jenkins, J., "A Closer Look at Switched Reluctance Motors," Charged Magazine, Cot/Nov 2012, pp. 26-28.
159 Ruoff, C., "A Closer Look at Torque Ripple," Charged Magazine, Jul/August 2015, pp. 22-29.
160 "First look at all-new Voltec propulsion system for 2G Volt; the only thing in common is a shipping cap," Green Car Congress, October 29, 2014. Retrieved May 2, 2016 from http://www.greencarcongress.com/2014/10/20141029-voltec.html.
161 "Chevrolet Introduces All-New 2016 Volt," General Motors Press Release, January 12, 2015. http://media.gm.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/Jan/naias/chevrolet/volt/0112-volt-2016-intro.html.
162 Morris, C., "2016 Chevy Volt: GM's top electrification engineers on designing the all-new EREV," https://chargedevs.com/features/2016-chevy-volt-gms-top-electrification-engineers-on-designing-the-all-new-erev/.
163 Anwar, M. et al., "Power Dense and Robust Traction Power Inverter for the Second-Generation Chevrolet Volt Extended-Range EV," SAE Int. J. Alt. Power. 4(1):145-152, 2015, doi: 10.4271/2015-01-1201.
164 Grewe, T., General Motors, "GM RWD PHEV Propulsion System for the Cadillac CT6 Sedan," SAE paper 2016-01-1159, presented at 2016 SAE Hybrid and Electric Vehicle Technologies Symposium, February 10, 2016.
165 Grewe, T., General Motors, "Chevrolet Malibu Hybrid Propulsion System," presented at 2016 SAE Hybrid and Electric Vehicle Technologies Symposium, February 10, 2016.
166 "Toyota Unveils Advanced Technologies in All-New Prius," http://pressroom.toyota.com/releases/2016+toyota+prius+technology.htm.

[167] Cole, J., "Exclusive: GM Exec Says Spark EV's 400 lb-ft of Torque No Misprint," May 2, 2013 (source confirmed by conversation with P. Savagian, February 2016). At http://insideevs.com/gm-general-says-spark-evs-400lb-ft-of-torque-no-misprint/.
[168] Whaling, C., "Market Analysis of Wideband Gap Devices in Car Power Electronics." Retrieved March 9, 2016 from http://tec.ieee.org/2014/10/31/market-analysis-wideband-gap-devices-car-power-electronics/.
[169] Kimura, T. et al., "High-power-density Inverter Technology for Hybrid and Electric Vehicle Applications," Hitachi Review Vol. 63 No. 2 (2014). Retrieved on March 31, 2016 from http://www.hitachi.com/rev/pdf/2014/r2014_02_106.pdf.
[170] Goreham, J., "Toyota reveals breakthrough that will increase future Prius MPG by 10%," Torque News. Retrieved May 2, 2016 from http://www.torquenews.com/1083/toyota-reveals-breakthrough-will-increase-future-prius-mpg-10#sthash.iIxVsn43.dpuf.
[171] Beg, F., "A Novel Design Methodology for a 1.5 KW DC/DC Converter in EV and Hybrid EV Applications," International Science Index, Electrical and Computer Engineering Vol:8, No:9, 2014.
[172] Al Sakka, M. et al., "DC/DC Converters for Electric Vehicles," in Electric Vehicles - Modelling and Simulations, Dr. Seref Soylu (Ed.), ISBN: 978-953-307-477-1, InTech, 2011. Available from: http://cdn.intechopen.com/pdfs-wm/19583.pdf.
[173] "Obama Administration Announces New Actions To Accelerate The Deployment of Electrical Vehicles and Charging Infrastructure," Press Release, The White House, November 3, 2016.
[174] Partial Consent Decree, in re: Volkswagen "Clean Diesel" Marketing, Sales Practices, and Products Liability Litigation, Case 3:15-md-02672-CRB Document 1605-1 Filed 06/28/16. Retrieved on November 7, 2016 from https://www.epa.gov/sites/production/files/2016-06/documents/vwpartialsettlement-cd.pdf
[175] "Fixing America's Surface Transportation Act—Designation of Alternative Fuel Corridors," Federal Register, Vol. 81, No. 141, Friday, July 22, 2016. See also: http://www.fhwa.dot.gov/environment/alternative_fuel_corridors/
[176] Safoutin, M., Cherry, J., McDonald, J., and Lee, S., "Effect of Current and SOC on Round-Trip Energy Efficiency of a Lithium-Iron Phosphate (LiFePO4) Battery Pack," SAE Technical Paper 2015-01-1186, 2015, doi:10.4271/2015-01-1186.
[177] Idaho National Laboratory, "Steady State Vehicle Charging Fact Sheet: 2015 Nissan Leaf," INL/EXT-15-34055. Downloaded Jan. 26, 2016 from http://avt.inel.gov/pdf/fsev/SteadyStateLoadCharacterization2015Leaf.pdf.
[178] Conlon, B., Blohm, T., Harpster, M., Holmes, A. et al., "The Next Generation "Voltec" Extended Range EV Propulsion System," SAE Int. J. Alt. Power.4(2):248-259, 2015, doi:10.4271/2015-01-1152.
[179] Raghavan, A., "SENSOR: Smart Embedded Network of Sensors with Optical Readout," PARC and LG Chem Power, presented at AABC 2014, February 2014.
[180] Herron, D., "Why Do Electric Cars Have Lead-Acid 12-Volt Batteries When Lithium Is Lighter?" PlugInCars.com, December 20, 2013. Retrieved from http://www.plugincars.com/why-do-electric-cars-have-lead-acid-12-volt-batteries-when-lithium-lighter-129118.html
[181] Webb, A., "Tesla Owners Encounter Problems with 12-Volt Battery," PlugInCars.com, January 22, 2014. Retrieved from http://www.plugincars.com/tesla-owners-encounter-ev-related-problems-12-volt-battery-129287.html
[182] Teslarati.com, "Why Tesla's lead acid 12V battery needs to be lithium-ion based," September 22, 2016. Retrieved from http://www.teslarati.com/why-tesla-12v-battery-needs-to-be-lithium-ion/
[183] TeslaMotorsClub.com, "Near annual replacement of 12V battery is typical according to Tesla Service Tech," user discussion thread, Jan 15, 2015. Retrieved from https://teslamotorsclub.com/tmc/threads/near-annual-replacement-of-12v-battery-is-typical-according-to-tesla-service-tech.41006/
[184] C&D Technologies, "Deep Cycle Series DCS-33H/DCS-33 Valve Regulated Lead Acid Battery for Deep Cycle Mobility Applications," Manufacturer Data Sheet, 41-7956.
[185] A123 Systems, A123 12V Starter Battery Information Sheet. Retrieved from http://www.a123systems.com/lithium-starter-battery.htm
[186] Weissler, P., "Hyundai targets Prius with new 'triple-electrified' Ioniq," SAE Automotive Engineering, March 30, 2016. Retrieved from http://articles.sae.org/14706/
[187] http://www.uscar.org/guest/partnership/1/us-drive.
[188] U.S. DRIVE Partnership, "US DRIVE Electrical and Electronics Technical Team Roadmap," June 2013. Down loaded on Dec. 23, 2015 from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf.
[189] U.S. DRIVE Partnership, "US DRIVE Electrical and Electronics Technical Team Roadmap," June 2013, pp. 7-8.
[190] Slenzak, J., "Next Generation Electrification Products: Focus on Integration and Cost Reduction," Bosch, The Battery Show 2015, Novi MI, September 15, 2015.

---

[191] cf. U.S. DRIVE Electrical and Electronics Technical Team Roadmap, p. 10.
[192] Kane, M., "Deep Dive: Chevrolet Bolt Battery Pack, Motor And More." Retrieved April 18, 2016 from http://insideevs.com/deep-dive-chevrolet-bolt-battery-pack-motor-and-more/.
[193] EPA, "Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," 2012, p. 3-52. See Docket ID EPA-HQ-OAR-2010-0799, docket item number EPA-HQ-OAR-2010-0799-12013.
[194] EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015," December 2015, p 72.
[195] EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015," December 2015, p 75.
[196] EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015," December 2015, p 48.
[197] Consumer Reports News, "Stop idling! Stop-start systems have great promise for saving fuel," June 29, 2012. Retrieved from http://www.consumerreports.org/cro/news/2012/06/stop-idling-stop-start-systems-have-great-promise-for-saving-fuel/index.htm.
[198] Martinez, M., "More cars getting stop-start despite driver resistance," The Detroit News, October 8, 2014. Retrieved from http://www.detroitnews.com/story/business/autos/2014/10/07/autos-stop-start-driver-resistance/16893597/.
[199] Murray, C., "GM Chooses Micro- Over Mild-Hybrid in New Malibu," Design News, October 16, 2013.
[200] Green Car Congress, "Schaeffler demo vehicle hits 2020 CAFE targets without electrification; 15% cut in fuel consumption; 48V hybrid system for 2025," January 27, 2014. Retrieved from http://www.greencarcongress.com/2014/01/20140127-schaeffler.html.
[201] Halvorson, B., " Ultracapacitor Resistance Breaking Down Among Automakers?" Green Car Reports, June 2, 2015. Retrieved from http://www.greencarreports.com/news/1098550_ultracapacitor-resistance-breaking-down-among-automakers.
[202] Bragman, A., "2014 Chevrolet Malibu: Frist Drive," Cars.com, October 11, 2013. Retrieved from https://www.cars.com/articles/2013/10/2014-chevrolet-malibu-first-drive/.
[203] Ford Motor Company, "70 Percent of Ford Lineup to Have Auto Start-Stop by 2017; Fuel Economy Plans Accelerate," Press Release, December 12, 2013.
[204] M. Everett, "Advancing Ultracapacitor Applications in Industrial and Transportation Applications," 2015 AABC, Detroit.
[205] Mazda, "Brake Energy Regeneration System: i-ELOOP continuously recovers kinetic energy as the vehicle decelerates and reuses it as electricity," retrieved on April 1, 2016 from http://www.mazda.com/en/innovation/technology/env/i-eloop/.
[206] Blessing, U., "GETRAG 48V: How much hybridization is possible with the new vehicle power?." 14th VDI Congress, 2014.
[207] FEV, "In-market Application of Start-Stop Systems in European Market," Final Report, P26844-01/ A1/ 01/ 61605, December 2011. Retrieved from http://www.theicct.org/sites/default/files/FEV_LDV%20EU%20Technology%20Cost%20Analysis_StartStop%20Overview.pdf.
[208] EPA, "Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," 2012, p. 3-52. See Docket ID EPA-HQ-OAR-2010-0799, docket item number EPA-HQ-OAR-2010-0799-12013.
[209] H-D Systems, "Future U.S. Trends in the Adoption of Light-Duty Automotive Technologies," Integrated Final Report, Prepared for: American Petroleum Institute, September 2013, p. 60.
[210] German, J., "Hybrid Vehicles: Technology Development and Cost Reduction," International Council on Clean Transportation (ICCT), Technical Brief No. 1, July 2015.
[211] Graf, F. et al., "AES: An Approach to an Integrated 12V/48V Energy Storage Solution," Proceedings of the 24th Aachen Colloquium Automobile and Engine Technology 2015, pp. 1077-1090.
[212] National Academy of Sciences, "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," 2015, Prepublication Copy, p. 4-39.
[213] Bilek, M., "2013 Chevrolet Malibu - Refreshed for 2013, Chevy's midsize offering gains refinement and features," DriveChicago.com. Retrieved May 5, 2016 from http://www.drivechicago.com/reviews/2013-chevrolet-malibu-refreshed-for-2013-chevys-midsize-offering-gains-refinement-and-features_2424.
[214] Edmunds.com, "Full Edmunds Expert Review: 2013 Chevrolet Malibu." Retrieved on May 5, 2016 from http://www.edmunds.com/chevrolet/malibu/2013/review/

[215] General Motors, "2013 Malibu Eco Is The Most Fuel-Efficient Malibu Ever," Press Release, December 12, 2011. http://media.gm.com/media/us/en/chevrolet/news.detail.html/content/Pages/news/us/en/2011/Dec/1212_malibu/1212_eassist.html.
[216] Gross, O., "Defining Energy Storage System Requirements Based upon Passenger Vehicle Fleet Needs," 2015 Battery Congress.
[217] General Motors, "GMC Introduces 2016 Sierra with eAssist," Retrieved March 9, 2016 from http://www.gm.com/mol/m-2016-feb-0225-sierra-eAssist.html.
[218] General Motors, "Chevrolet Introduces 2016 Silverado with eAssist," Retrieved March 11, 2016 from http://www.gm.com/mol/m-2016-feb-0225-silverado-eAssist.html.
[219] FEV, "Light-Duty Vehicle Technology Cost Analysis: 2013 Chevrolet Malibu ECO with eAssist BAS Technology Study," Report FEV P311264, Contract No. EP-C-12-014, WA 1-9 (January 2014). http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P100EWVL.txt.
[220] Howard, B., "Honda Fit: 86 mpg from the next hyper-efficient hybrid," Extreme Tech, August 8, 2013. Retrieved from http://www.extremetech.com/extreme/163462-honda-fit-86-mpg-from-the-next-hyper-efficient-hybrid.
[221] Kok, D., Ford Motor Company, "Power of Choice: The Role of Hybrid Vehicle Technology in Meeting Customer Expectations," The Battery Show 2014, September 18, 2014.
[222] Duren, A., A123 Systems, "48V Battery System Design for Mild Hybrid Applications," SAE Hybrid & Electric Vehicle Technologies Symposium, February 2016.
[223] Bosch, "The hybrid for everyone: Bosch's 48-volt system makes sense even in compact vehicles," Press Release, September 4, 2015. Retrieved April 1, 2016 from http://www.bosch-presse.de/presseforum/details.htm?txtID=7384&locale=en.
[224] MacRae, C., "February 2015 management briefing: 48V mild hybrids (3)," retrieved from http://www.just-auto.com/analysis/48v-mild-hybrids-3_id156298.aspx.
[225] Fiat Chrysler Automobiles, "Business Plan Update 2014-2018," January 27, 2016. Retrieved from http://www.fcagroup.com/en-US/investor_relations/events_presentations/quarterly_results_presentations/FCA_2014_18__Business_Plan_Update.pdf.
[226] Sanchez, E., "Ram, Jeep Hybrids Revealed in FCA Future Business Plan," Truck Trend Network, January 27, 2016. Retrieved from http://www.trucktrend.com/news/1601-ram-jeep-hybrids-revealed-in-fca-future-business-plan/.
[227] Irwin, J., "Supplier Schaeffler in 48V Mild-Hybrid Vanguard," Wards Auto, January 15, 2016. Retrieved from http://wardsauto.com/technology/supplier-schaeffler-48v-mild-hybrid-vanguard.
[228] Voelcker, J., "2016 Hyundai Tucson Shows Two Different Hybrid Concepts In Geneva," Green Car Reports, March 17, 2015. Retrieved from http://www.greencarreports.com/news/1097268_2016-hyundai-tucson-shows-two-different-hybrid-concepts-in-geneva.
[229] Harrop, P., "48V vehicle systems becoming significant," IDTechEx.com, August 12, 2015. Retrieved from http://www.electricvehiclesresearch.com/articles/8266/48v-vehicle-systems-becoming-significant
[230] Wiesenberger, J., Continental, "The Evolving EV and Hybrid Roadmap," The Battery Show 2015, Novi, Michigan, September 15, 2015.
[231] Stenzel, U., "48V Mild Hybrid Systems: Market Needs and Technical Solutions," AVL Powertrain Engineering, AVL UK Expo 2014. Retrieved March 7, 2016 from https://www.avl.com/documents/10138/1379144/AVL_UK_Expo_48V_Mild_Hybrid_Systems.pdf.
[232] Brooke, L., "Ford accelerates research on 48-V mild hybrid systems," SAE International, February 12, 2015. Retrieved from http://articles.sae.org/13908/.
[233] Bosch, "The hybrid for everyone: Bosch's 48-volt system makes sense even in compact vehicles," Press Release, September 4, 2015. Retrieved April 1, 2016 from http://www.bosch-presse.de/presseforum/details.htm?txtID=7384&locale=en.
[234] Berman, B., "Hybrid Car Affordability Leaps Forward with P2 Technology," April 19, 2011. Retrieved from http://www.hybridcars.com/hybrid-car-affordability-leaps-forward-p2-technology-29761/.
[235] Truett, R. et al., "Electric turbocharger eliminates lag, Valeo says," Automotive News, August 3, 2014. Retrieved from http://www.autonews.com/article/20140803/OEM10/308049992/electric-turbocharger-eliminates-lag-valeo-says.
[236] Hanlon, M., "Controlled Power Technologies shows 48V electric supercharger," Gizmag, October 4, 2011. Retrieved from http://www.gizmag.com/controlled-power-technologies-48v-electric-vtes-supercharger/20037/.
.

---

237 EPA, "Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," 2012, p. 3-52. See Docket ID EPA-HQ-OAR-2010-0799, docket item number EPA-HQ-OAR-2010-0799-12013.
238 Gehm, R., "Inside Honda's new two-motor 50-mpg Accord Hybrid," SAE International, December 18, 2013. Retrieved from http://articles.sae.org/12666/.
239 Sessions, R., "2015 Toyota Camry SE Hybrid," Car and Driver, January 2015. Retrieved from http://www.caranddriver.com/reviews/2015-toyota-camry-hybrid-test-review.
240 Green Car Congress, "Toyota details powertrain advances in Gen4 Prius; available E-Four system for all-wheel drive (not for US)," October 13, 2015. Retrieved from http://www.greencarcongress.com/2015/10/20151013-prius.html.
241 "Light Duty Technology Cost Analysis, Power-Split and P2 Hybrid Electric Vehicle Case Studies," Report EPA-420-R-11-015, November 2011.https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EG1R.PDF?Dockey=P100EG1R.PDF..
242 German, J., "Hybrid Vehicles Technology Development and Cost Reduction," Technology Brief, No. 1, July 2015, ICCT, p. 6.
243 National Academy of Sciences (NAS), National Research Council (NRC), "Overcoming Barriers to Deployment of Plug-in Electric Vehicles," NAS Committee on Overcoming Barriers to Electric-Vehicle Deployment, 2015.
244 New Qualified Plug-in Electric Drive Motor Vehicles, 26 U.S.C. § 30D.
245 See https://www.fueleconomy.gov/feg/taxphevb.shtml.
246 Cobb, J., "How Long Does the 2017 Chevy Bolt Have Before Federal Credits Begin Fading Away?" HybridCars.com, January 13, 2016. Retrieved on January 27, 2016 from http://www.hybridcars.com/how-long-does-the-2017-chevy-bolt-have-before-federal-credits-begin-fading-away/.
247 Shelton, S., "US-Bound BMW 330e and X5 xDrive40e PHEVs Bow In LA," HybridCars.com, November 20, 2015. Retrieved from http://www.hybridcars.com/us-bound-bmw-330e-and-x5-xdrive40e-phevs-bow-in-la/.
248 Cobb, J., "Exclusive: 2017 Mitsubishi Outlander PHEV Postponed To Next Summer," HybridCars.com, July 28, 2016. Retrieved from http://www.hybridcars.com/exclusive-2017-mitsubishi-outlander-phev-postponed-to-next-summer/
249 Berman, B., "New Target Date for Outlander PHEV Introduction: Spring 2016", Retrieved April 25, 2016 from http://www.plugincars.com/new-target-date-outlander-phev-introduction-spring-2016-130848.html.
250 Halvorson, B., "2017 Chrysler Pacifica Hybrid: More Details On 30-Mile Plug-In," Jan. 20, 2016, http://www.greencarreports.com/news/1101960_2017-chrysler-pacifica-hybrid-more-details-on-30-mile-plug-in.
251 Cole, J., "Upcoming Honda PHEV To Have 40 Miles Of Electric Range," http://insideevs.com/upcoming-honda-phev-40-miles-electric-range/.
252 General Motors, "The Results are In: More Range for the 2016 Volt," Press Release, August 4, 2015. http://media.chevrolet.com/media/us/en/gm/news.detail.html/content/Pages/news/us/en/2015/aug/0804-volt-range.html.
253 California Air Resources Board, "CCR Section 1962.2: 2018 and Subsequent Model Year Requirements," July 2014. Downloaded on May 26, 2016 from http://www.arb.ca.gov/msprog/zevprog/zevregs/1962.2_Clean.pdf.
254 World Bank, "The China New Energy Vehicles Program: Challenges and Opportunities," Report 61259, April 2011. Available at http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/04/20/000356161_20110420054039/Rendered/PDF/612590WP0PRTM01BOX358342B01PUBLIC11.pdf.
255 International Council on Clean Transportation, "Renewed and Enhanced Subsidies for Energy-Efficient Vehicles in China," Policy Update, November 2013. Available at http://www.theicct.org/sites/default/files/publications/ICCTupdate_CNsubsidies_nov2013.pdf.
256 Anderman, M., "xEV Market Drivers and Trends; the Role of Regulations, Incentives, and Technology," presented at 2015 Advanced Automotive Batteries Conference, June 17, 2015.
257 Cadillac, "Cadillac CT6 PlugIn Sets New Electric Luxury EV Performance Benchmark," Press Release, April 19, 2015. Retrieved on 10/23/2015 from http://media.cadillac.com/media/cn/en/cadillac/news.detail.html/content/Pages/news/cn/en/2015/april/0419_PHEV.html.
258 Cole, J., "Washington Expands $3,100 Electric Vehicle Incentive Program." Retrieved on April 19, 2016 from http://insideevs.com/washington-launches-3100-electric-vehicle-incentive-program/.
259 Grewe, T., "Generation Two Voltec Drive System," presented at SAE Hybrid and Electric Vehicle Symposium, February 2015.
260 See Table 3.5-25 of RIA, 2017-2025 FRM.
261 Green Car Congress, "Navigant Research Leaderboard puts LG Chem as leader for

Li-ion batteries for transportation," November 25, 2015. Retrieved from http://www.greencarcongress.com/2015/11/20151125-navigant.html.
[262] Navigant Research, "Navigant Research Leaderboard Report: Lithium Ion Batteries for Transportation," Summary Page. Retrieved from https://www.navigantresearch.com/research/navigant-research-leaderboard-report-lithium-ion-batteries-for-transportation.
[263] Tesla Motors, "Tesla's Comments to the Draft Technical Assessment Report," submitted to Docket EPA-HQ-OAR-2015-0827, September 26, 2016.
[264] AutoBlog.com, "Analyst predicts 30-80k Chevy Bolt sales in first year," May 9, 2016. Retrieved from http://www.autoblog.com/2016/05/09/2017-chevy-bolt-sales-prediction/
[265] Voelcker, J., "2017 Chevy Bolt EV sales could go as high as 80,000, says analyst," Green Car Reports, May 12, 2016. Retrieved from http://www.greencarreports.com/news/1103922_2017-chevy-bolt-ev-sales-could-go-as-high-as-80000-says-analyst.
[266] Hunt, T., "Why Tesla's Model 3 Could Be the New Model T," GreenTechTedia.com, April 11, 2016. Retrieved from https://www.greentechmedia.com/articles/read/Why-Teslas-Model-3-Could-Be-The-New-Model-T
[267] Consumer Federation of America, "New Data Shows Consumer Interest in Electric Vehicles Is Growing," Press Release, September 19, 2016.
[268] Korosec, K., "GM Puts Self-Driving Car Push Into a Higher Gear," Fortune, January 29, 2016. Retrieved from http://fortune.com/2016/01/29/gm-self-driving-car-division/.
[269] Korosec, K., "GM Is Giving Lyft Drivers First Dibs on Its New All-Electric Chevy Bolt," Fortune, July 11, 2016. Retrieved from http://fortune.com/2016/07/11/gm-lyft-drivers-chevy-bolt/.
[270] Davies, A., "We Take a Ride in the Self-Driving Uber Now Roaming Pittsburgh," Wired, September 14, 2016. Retrieved from https://www.wired.com/2016/09/self-driving-autonomous-uber-pittsburgh/
[271] Gardner, G., "The self-driving revolution will be mostly electric," Detroit Free Press, September 21, 2106. Retrieved from http://www.freep.com/story/money/cars/2016/09/18/self-driving-revolution-mostly-electric/90410520/.
[272] InsideEVs.com, "Monthly Plug-In Sales Scorecard," retrieved on November 2, 2016 from http://insideevs.com/monthly-plug-in-sales-scorecard/.
[273] Partial Consent Decree, in re: Volkswagen "Clean Diesel" Marketing, Sales Practices, and Products Liability Litigation, Case 3:15-md-02672-CRB Document 1605-1 Filed 06/28/16. Retrieved on November 7, 2016 from https://www.epa.gov/sites/production/files/2016-06/documents/vwpartialsettlement-cd.pdf.
[274] "Fixing America's Surface Transportation Act—Designation of Alternative Fuel Corridors," Federal Register, Vol. 81, No. 141, Friday, July 22, 2016. See also: http://www.fhwa.dot.gov/environment/alternative_fuel_corridors/.
[275] Falkenberg-Hull, E., "Automotive Minute: Nationwide electric vehicle charging network expanding," Atlanta Business Chronicle, September 20, 2016. Retrieved from http://www.bizjournals.com/atlanta/news/2016/09/20/automotive-minute-nationwide-electric-vehicle.html.
[276] Kurylko, D. T., "BMW will boost i3's range," Automotive News, January 18, 2016. Downloaded on Jan. 19, 2016 from http://www.autonews.com/article/20160118/OEM05/301189994/bmw-will-boost-i3s-range.
[277] BMW Group, "The new 2017 BMW i3 (94 Ah): More range paired to high-level dynamic performance," Press Release, May 2, 2016. Retrieved on May 2, 2016 from https://www.press.bmwgroup.com/usa/article/detail/T0259560EN_US/the-new-2017-bmw-i3-94-ah-more-range-paired-to-high-level-dynamic-performance.
[278] Autoblog, "VW e-Golf will get 30% range boost thanks to improved batteries," January 9, 2016. Downloaded on Jan. 19, 2016 from http://www.autoblog.com/2016/01/09/volkswagen-e-golf-30-percent-range-increase-new-batteries/.
[279] Ford Motor Company, "Ford Investing $4.5 Billion in electrified Vehicle Solutions, Reimagining How To Create Future Vehicle User Experiences," Press Release, December 10, 2015. Retrieved on April 19, 2016 from https://media.ford.com/content/fordmedia/fna/us/en/news/2015/12/10/ford-investing-4-5-billion-in-electrified-vehicle-solutions.pdf.
[280] Hyundai Motor America, "2017 Hyundai Ioniq Model Lineup Makes U.S. Debut at New York International Auto Show," Press Release, March 23, 2016. Retrieved on May 5, 2016 from http://www.hyundainews.com/us/en/print/45159.
[281] Tesla Motors website, Model 3 reservation page. Retrieved on April 19, 2016 from https://www.teslamotors.com/model3.
[282] Bunkley, N., "Ford plans EV to compete with Chevy Bolt, Tesla Model 3, Fields confirms," Automotive News, April 28, 2016. Retrieved on November 2, 2016 from

---

http://www.autonews.com/article/20160428/OEM05/160429821/fields-confirms-ford-planning-ev-to-compete-with-chevy-bolt-tesla.
[283] Taylor, M., "Everything we know about Volkswagen's next Golf," retrieved November 2, 2016 from http://www.autoblog.com/2016/02/05/volkswagen-golf-eighth-generation-information/
[284] Davies, A., "Audi's Plan to Make an Electric SUV with a 300-Mile Range," Wired, August 14, 2015. Retrieved on November 2, 2016 from https://www.wired.com/2015/08/audis-plan-make-electric-suv-300-mile-range/.
[285] Tesla Motors, "New Tesla Model S Now the Quickest Production Car in the World," August 23, 2016. Retrieved on November 2, 2016 from https://www.tesla.com/blog/new-tesla-model-s-now-quickest-production-car-world.
[286] Ayre, J., "Tesla CEO Elon Musk: 100 kWh Battery Pack Probably As Large As We're Going," Clean Technica, September 16, 2016. Retrieved on November 2, 2016 from https://cleantechnica.com/2016/09/16/tesla-ceo-elon-musk-100-kwh-battery-pack-probably-large-going/.
[287] Tesla Motors, "Roadster 3.0 Battery Upgrade." Retrieved on November 2, 2016 from http://shop.teslamotors.com/products/roadster-3-0-upgrade.
[288] Tesla Motors Press Release, "Tesla Model S Sales Exceed Target," March 31, 2013. http://www.teslamotors.com/de_AT/blog/tesla-model-s-sales-exceed-target.
[289] Konekamp, A., "The Tesla Model S Battery: A Battery Pack Analysis Study;" AVL List GmbH, 2015 Advanced Automotive Battery Conference, Detroit MI June 15-19, 2015.
[290] Rugh, J., Hovland, V. and Andersen, S., "Significant Fuel Savings and Emissions Reductions by Improving Vehicle Air Conditioning," National Renewable Energy Laboratory, NREL/CP-5400-62232, presented at the 15th Annual Earth Technologies Forum and Mobile Air Conditioning Summit, April 15, 2004.
[291] Kim, N. et al., "Modeling Electrified Vehicles Under Different Thermal Conditions," Argonne National Laboratory, presented at Society of Automotive Engineers Thermal Management Systems Symposium, September 29-October 1, 2015.
[292] Chaney, L., et al., "Climate Control Load Reduction Strategies for Electric Drive Vehicles in Cold Weather," National Renewable Energy Laboratory, presented at Society of Automotive Engineers Thermal Management Systems Symposium, September 29-October 1, 2015.
[293] Chen, K., Bozeman, J., Wang, M., Ghosh, D. et al., "Energy Efficiency Impact of Localized Cooling/Heating for Electric Vehicle," SAE Technical Paper 2015-01-0352, 2015, doi: 10.4271/2015-01-0352.
[294] Bunkley, N., "Ford plans EV to compete with Chevy Bolt, Tesla Model 3, Fields confirms," Automotive News, April 28, 2016. Retrieved on November 2, 2016 from http://www.autonews.com/article/20160428/OEM05/160429821/fields-confirms-ford-planning-ev-to-compete-with-chevy-bolt-tesla.
[295] Hall, L., "2017 Renault Zoe Getting New 200-Mile Battery - Nissan Leaf to Follow?" HybridCars.com, September 28, 2016. Retrieved from http://www.hybridcars.com/2017-renault-zoe-getting-new-200-mile-battery-nissan-leaf-to-follow/.
[296] Malliaris, A.C., Hsia, H., and Gould, H.; "Concise description of auto fuel economy and performance in recent model years," Society of Automotive Engineers, Paper 760045 (1976).
[297] U.S. EPA, *Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015*, Report EPA-420-R-15-016, December 2015, p. 35.
[298] Green Car Congress, "Kia using SK Innovation NCM Li-ion cells in Soul EV," February 24, 2014. Retrieved from http://www.greencarcongress.com/2014/02/20140224-kia.html.
[299] Howell, D., "U.S. DOE Electric Drive Vehicle Battery R&D Impacts, Progress, and Plans," AABC 2015, Detroit MI, June 2015.
[300] Weissler, P., "Electronics diverge in engineering Ford's hybrid C-Max and plug-in Energi," SAE International, January 9, 2013. Retrieved May 5, 2016 from http://articles.sae.org/11705/
[301] Kessen, Jeff, and Duren, Angela, "System Design Solutions for 48V Lithium-Ion Batteries," AABC 2015, AABTAM Session 2, June 18, 2015.
[302] Nuspl, G. et al., "Developing Battery Materials for Next Generation Applications," The Battery Show 2015, Novi MI, 2015.
[303] Oury, A., General Motors, "2016 Chevrolet Malibu Hybrid Battery Pack," presented at AABC 2015, Detroit Michigan, June 18, 2015.
[304] Voelcker, J., "2016 Toyota Prius: A Few Details On Engine, Hybrid System Released," Green Car Reports, October 12, 2015. Retrieved on May 5, 2016 from http://www.greencarreports.com/news/1100436_2016-toyota-prius-a-few-details-on-engine-hybrid-system-released.
[305] Tajitsu, N. et al.,"Warming to lithium-ion, Toyota charges up its battery options," Reuters, October 30, 2016. Retrieved on November 2, 2016 from http://www.reuters.com/article/us-toyota-batteries-idUSKBN12U0ZH

306 Sion Power, "Sion Power's Licerion High Energy Batteries," The Battery Show 2015, Novi, MI, September 2015.
307 PR Newswire, "Anesco and OXIS to Release Lithium Sulfur Battery Storage by 2016," Press Release, July 14, 2015. Retrieved from http://www.prnewswire.com/news-releases/anesco-and-oxis-to-release-lithium-sulfur-battery-storage-by-2016-514802521.html.
308 Morris, C., "OXIS Energy achieves 300 Wh/kg with lithium-sulfur cell," Charged Magazine, Nov/Dec 2014, p. 21. Retrieved from https://chargedevs.com/newswire/oxis-energy-achieves-specific-energy-of-300-whkg-with-lithium-sulfur-cell/.
309 Ruoff, C., "Tesla Tweaks its Battery Chemistry: A Closer Look at Silicon Anode Development," Charged Magazine, Jul/Aug 2015, p. 30.
310 Sawers, P., "Dyson acquires Sakti3 for $90M to help commercialize ‘breakthrough’ solid-state battery tech." Retrieved on April 1, 2016 from http://venturebeat.com/2015/10/19/dyson-acquires-sakti3-for-90m-to-help-commercialize-breakthrough-solid-state-battery-tech/.
311 Vaughan, A and Carrington, D., "Dyson developing an electric car, according to government documents," The Guardian, March 23, 2016. Retrieved on April 1, 2016 from http://www.theguardian.com/environment/2016/mar/23/dyson-developing-electric-car-government-documents.
312 Seeo, "Bosch Has Groundbreaking Battery Technology for Electric Vehicles." Retrieved on April 19, 2016 from http://www.seeo.com/news/bosch-has-groundbreaking-battery-technology-for-electric-vehicles/
313 Brooke, L., "Battery guru: Future of 18650 cells unclear beyond Tesla S," SAE International, February 17, 2014. Retrieved on May 5, 2016 from http://articles.sae.org/12833/.
314 Business Wire, "Samsung SDI to Supply Cylindrical EV Batteries to JAC Motors," November 23, 2015. Retrieved from http://www.businesswire.com/news/home/20151123005451/en/Samsung-SDI-Supply-Cylindrical-EV-Batteries-JAC.
315 Anderman, M., "Battery Packs of Modern xEVs: A Comprehensive Engineering Assessment: Extract," slide 18, Total Battery Consulting, 2016.
316 Element Energy, "Cost and Performance of EV Batteries: Final Report for The Committee on Climate Change," March 21, 2012. Retrieved from http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/06/CCC-battery-cost_-Element-Energy-report_March2012_Finalbis.pdf.
317 Faguy, Peter, "Overview of the DOE Advanced Battery R&D Program," presented at the 2015 U.S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, June 8, 2015.
318 Yeow, K. et al., "3D Thermal Analysis of Li-ion Battery Cells with Various Geometries and Cooling Conditions Using Abaqus," 2012 SIMULIA Community Conference.
319 Brooke, L., "GM unveils more efficient 2016 Volt powertrain," October 29, 2014. Retrieved on May 5, 2016 from http://articles.sae.org/13666/.
320 Nissan, "2016 Nissan LEAF Press Kit: Overview." Retrieved on May 5, 2016 from http://nissannews.com/en-US/nissan/usa/presskits/us-2016-nissan-leaf-press-kit.
321 Kwon, Jason; "Samsung's Automotive Battery Strategy," Samsung SDI, AABC 2015, June 18, 2015.
322 Kia Motors, "Advanced battery pack for new Soul EV," Press Release, February 24, 2014. Retrieved April 4, 2016 from https://press.kia.com/eu/press/products/14_02_25_22%20-%20geneva%20soul%20ev%20batteries/.
323 Kia Motors America, "Kia Emergency Response Guide: Soul EV," September 2014.
324 Green Car Congress, "New 2016 Nissan LEAF with available 30 kWh pack for 107 milerange," September 10, 2015. Retrieved from http://www.greencarcongress.com/2015/09/20150910-leaf.html.
325 Schmitt, B., "2nd gen Leaf expected 2018: 60kWh NMC battery, 300 mile range, autonomous, CFRP." Retrieved January 27, 2016 from http://dailykanban.com/2015/10/2nd-gen-leaf-expected-2018-60kwh-nmc-battery-300-mile-range-autonomous-cfrp/.
326 Green Car Reports, "Next Nissan Leaf confirmed for 60-kwh battery, 200 miles of range," June 22, 2016. Retrieved on November 2, 2016 from http://www.greencarreports.com/news/1104610_next-nissan-leaf-confirmed-for-60-kwh-battery-200-miles-of-range.
327 Halvorson, B., "Nissan's 60-kWh, 200-Mile Battery Pack: What We Know So Far," Green Car Reports, November 5, 2015. Retrieved from http://www.greencarreports.com/news/1100775_nissans-60-kwh-200-mile-battery-pack-what-we-know-so-far.
328 General Motors, "Drive Unit and Battery at the Heart of Chevrolet Bolt EV," Press Release, Jan. 11, 2016. Retrieved on January 27, 2016 from http://media.chevrolet.com/media/us/en/chevrolet/home.detail.html/content/Pages/news/us/en/2016/Jan/naias/chevy/0111-bolt-du.html.

[329] Markel, T., National Renewable Energy Laboratory, "Plug-In HEV Vehicle Design Options and Expectations," NREL/PR-540-40630, presented at ZEV Technology Symposium, California Air Resources Board, Sacramento CA, September 27, 2006.
[330] McGrath, P., "Advanced Management and Protection of Energy Storage Devices (AMPED)," presented at The Battery Show 2015, Novi MI, September 17, 2015.
[331] Brown, Carlton; "Generation 2 Lithium-Ion Battery Systems: Technology Trends and KPIs," Robert Bosch Battery Systems, 2015 Advanced Automotive Battery Conference, Detroit MI June 15-19, 2015.
[332] "Informal Testing of 2013 Volkswagen Jetta Hybrid Battery Usage," Memo to Docket EPA-HQ-OAR-2015-0827, June 28, 2016.
[333] Smith, K. et al., "Predictive Models of Li-ion Battery Lifetime," National Renewable Energy Laboratory, 2015 Advanced Automotive Battery Conference, Detroit MI June 15-19, 2015.
[334] "2016 Chevrolet Volt Battery," 2015 Advanced Automotive Battery Conference, Detroit MI June 18, 2015.
[335] ANL Advanced Powertrain Research Facility (APRF), http://www.anl.gov/energy-systems/group/downloadable-dynamometer-database.
[336] Noland, D., " Life With Tesla Model S: Battery Degradation Update," Green Car Reports, October 26, 2015. Retrieved from http://www.greencarreports.com/news/1100603_life-with-tesla-model-s-battery-degradation-update/page-2.
[337] Idaho National Laboratory, "Vehicle Testing - Light Duty - BEV" (website). See https://avt.inl.gov/vehicle-type/bev.
[338] MyKiaSoulEV.com, topic on High Voltage Battery System. See http://www.mykiasoulev.com/forum/viewtopic.php?p=1923.
[339] BMW Group, "BMW i3 Technical Data." See http://www.bmw.com/com/en/newvehicles/i/i3/2015/showroom/technical_data.html.
[340] Idaho National Laboratory, "Battery Pack Laboratory Testing Results, 2014 BMW i3 EV - VIN 5486," retrieved from https://avt.inl.gov/sites/default/files/pdf/fsev/batteryi5486.pdf.
[341] Idaho National Laboratory, "Battery Pack Laboratory Testing Results, 2014 BMW i3 EV - VIN 5626," retrieved from https://avt.inl.gov/sites/default/files/pdf/fsev/batteryi5626.pdf.
[342] Idaho National Laboratory, "Battery Pack Laboratory Testing Results, 2014 BMW i3 EV - VIN 5655," retrieved from https://avt.inl.gov/sites/default/files/pdf/fsev/batteryi5655.pdf.
[343] Idaho National Laboratory, "Battery Pack Laboratory Testing Results, 2014 BMW i3 EV - VIN 5658," retrieved from https://avt.inl.gov/sites/default/files/pdf/fsev/batteryi5658.pdf.
[344] General Motors, "Brownstown Battery Assembly Expands Capabilities, Will build battery system for 2015 Chevrolet Spark EV," Press Release, May 14, 2014. Retrieved from http://media.chevrolet.com/media/us/en/chevrolet/news.detail.html/content/Pages/news/us/en/2014/May/0514-brownstown.html.
[345] Uchida, T., "Analysis on Customers' Usage Data of Electric Vehicles," Honda R&D Co. Ltd. Automobile R&D Center, 2015 Advanced Automotive Battery Conference, Detroit MI, June 15-19, 2015.
[346] Lee, J., "Integrated Cabin and Battery Thermal Management System," Hanon Systems, presented at SAE 2015 Thermal Management Systems Symposium, Troy, MI, Sept. 30, 2015.
[347] Wawzyniak, M., "Battery Thermal Management Architectures and Components," MAHLE Behr GmbH & Co KG, presented at SAE 2015 Thermal Management Systems Symposium, Troy, MI, Sept. 30, 2015.
[348] Jeckel, A.; Beste, F., and Glossman, T., "Thermal Management of the High Voltage Battery," Daimler AG, presented at SAE 2015 Thermal Management Systems Symposium, Troy, MI, Sept. 30, 2015.
[349] Gross, O. and Clark, S., "Battery Thermal Management in xEVs: Session Introduction," Fiat Chrysler Automobiles, presented at AABC 2015, Detroit MI, June 2015.
[350] Bower, G., "Chevy Bolt 200 Mile EV Battery Cooling and Gearbox Details," InsideEVs.com, January 18, 2016. Retrieved from http://insideevs.com/chevy-bolt-200-mile-ev-battery-cooling-and-gearbox-details-bower/.
[351] Doggett, S., "Leaf's Batteries 'More Primitive' Than Those in Tesla's First Prototype, Musk Says," Edmunds Auto Observer, August 10, 2010. Retrieved from http://www.edmunds.com/autoobserver-archive/2010/08/leafs-batteries-more-primitive-than-those-in-teslas-first-prototype-musk-says.htm.l.
[352] Siry, D., "In Race to Market, Nissan's Electric Car Takes Shortcuts," Wired.com, January 22, 2010. Retrieved from http://www.wired.com/2010/01/nissan-leaf-2./.
[353] Moloughney, T., "No Active Thermal Management: Did Nissan Make the Right Call?" Retrieved from http://www.plugincars.com/no-active-thermal-management-did-nissan-make-right-call.html.

[354] Halvorson, B., "Nissan Leaf Likely To Get 'Hot Weather' Battery In Next Year," Green Car Reports, November 26, 2013. Retrieved from http://www.greencarreports.com/news/1088715_nissan-leaf-likely-to-get-hot-weather-battery-in-next-year.
[355] Wood, S., "Leveraging Automotive Lithium-Ion Technology for Commercial and Industrial Applications," Johnson Controls, presented at AABC 2015, Detroit MI, June 2015.
[356] Porsche, "Porsche Mission E," Press Release, September 14, 2015. Retrieved from http://newsroom.porsche.com/en/products/iaa-2015-porsche-mission-e-mobility-all-electrically-concept-car-11391.html.
[357] See Nelson, P. et al. "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric Drive Vehicles," p. 19 and p. 23.
[358] Wu, Y., "Assembly Processes for Lithium-Ion Batteries, 14.1.3. Coating Process," in *Lithium-Ion Batteries: Fundamentals and Applications*, Volume 4 of Electrochemical Energy Storage and Conversion, CRC Press (2015), p. 483.
[359] Gallagher, K., "PHEV and EV Battery Performance and Cost Assessment," Argonne National Laboratory, 2015 U.S. Department of Energy Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting, June 2015.
[360] Kia Motors, "Advanced Battery Pack for Kia Soul EV," Press Release, February 24, 2014. Retrieved on January 27, 2016 from http://www.kianewscenter.com/news/global-news/advanced-battery-pack-for-kia-soul-ev-/s/45548fc8-7279-4da3-81b2-d30df557420c.
[361] Kane, M., "Samsung SDI Presents Batteries That Enable 370 Miles (600 km) Of Range At 2016 NAIAS," retrieved January 27, 2016 from http://insideevs.com/samsung-sdi-presents-batteries-that-enable-370-miles-600-km-of-range-at-2016-naias/.
[362] Samsung SDI, "Samsung SDI Aims to Drive Battery Business Growth in North American Automobile Market With Its Top Technology Leadership," Press Release, Business Wire, January 11, 2016. Retrieved January 27, 2016 from http://www.businesswire.com/news/home/20160111005560/en/Samsung-SDI-Aims-Drive-Battery-Business-Growth.
[363] Rauwald, C., "VW to Add Flat Batteries to Boost Sales of Electric Vehicles," Bloomberg Business, December 13, 2015. Retrieved on January 27, 2016 from http://www.bloomberg.com/news/articles/2015-12-13/vw-developing-new-technology-to-integrate-flat-batteries-in-cars-ii4eee5d.
[364] Nelson, Paul A.; Ahmed, Shabbir; Gallagher, Kevin G., and Dees, Dennis W., "Cost Savings for Manufacturing Lithium Batteries in a Flexible Plant," Pre-publication draft, Argonne National Laboratory, 2015.
[365] Corrigan, D., "XALT Energy Lithium-Ion Batteries for Heavy Duty Vehicle and Marine Applications," AABC 2015, June 18, 2015.
[366] Paul, J., "Impact of Standardized Module Design - Commercial PEV and Second Life ESS Applications," AABC 2015, June 18, 2015.
[367] Cobb, J., "'Not a compliance car,' GM says 2017 Chevy Bolt can meet demand of over 50,000 per year," HybridCars.com, January 14, 2016. Downloaded on January 27, 2016 from http://www.hybridcars.com/not-a-compliance-car-gm-says-2017-chevy-bolt-production-capacity-exceeds-50000-per-year/.
[368] Roland Berger, "Consolidation Across the Li-Ion Battery Market Gaining Speed," Press Release, October 19, 2012. Retrieved from http://www.rolandberger.us/news/2012-10-19-Li-ion-Batteries-Bubble.html.
[369] Ramsey, M., "Auto Industry's Ranks of Electric-Car Battery Suppliers Narrow," Wall Street Journal, August 20, 2015.
[370] Green Car Congress, "Navigant Research ranks LG Chem as top automotive Li-ion battery manufacturer," June 25, 2013. Retrieved from http://www.greencarcongress.com/2013/06/navigant-20130625.html.
[371] Bathion, Michael; "Wanxiang Wins U.S. Approval to Buy Battery Maker A123," Bloomberg News, January 30, 2013. Retrieved Oct. 28, 2015 from http://www.bloomberg.com/news/articles/2013-01-29/wanxiang-wins-cfius-approval-to-buy-bankrupt-battery-maker-a123.
[372] Business Wire, "LG Chem, Panasonic, and Samsung SDI Score Highest in Assessment of Lithium Ion Battery Manufacturers, According to Navigant Research," Press Release, December 3, 2015. Retrieved from http://www.businesswire.com/news/home/20151203005014/en/.
[373] Ogura, K., "LG Chem, Tesla tie-up could jolt Panasonic," Nikkei Asian Review, October 28, 2015. Retrieved from http://asia.nikkei.com/Business/Deals/LG-Chem-Tesla-tie-up-could-jolt-Panasonic?page=1
[374] Business Wire, "Samsung SDI to Acquire Magna International's Battery Pack Business," Press Release, February 23, 2015. Retrieved on May 6, 2016 from http://www.businesswire.com/news/home/20150223005533/en/Samsung-SDI-Acquire-Magna-International%E2%80%99s-Battery-Pack.

[375] Pfanner, E. and Landers, P.; "Nissan Considers Shift to LG Chem Batteries," The Wall Street Journal, July 16, 2015. Retrieved on May 6, 2016 from https://www.linkedin.com/pulse/nissan-considers-shift-lg-chem-batteries-john-e-halajko.
[376] Kim, Y., "Tesla approaches LG, Samsung for Model 3 batteries," The Korea Times, May 17, 2016. Retrieved on May 19, 2016 from http://www.koreatimes.co.kr/www/news/tech/2016/05/133_204903.html.
[377] Evans, K., "The Future of Electric Vehicles: Setting the Record Straight on Lithium Availability," Journal of Energy Security, August 27 2009.
[378] Boston Consulting Group, "Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020," January 7, 2010.
[379] Gaines, L. and Cuenca, R., "Costs of Lithium-Ion Batteries for Vehicles," Argonne National Laboratory ANL/ESD-42, May 2000.
[380] Hiscock, J., "Australian lithium miners in pole position as price nears sweet spot," Nikkei Asian Review, July 28, 2016. Retrieved from http://asia.nikkei.com/Business/Trends/Australian-lithium-miners-in-pole-position-as-price-nears-sweet-spot?page=1.
[381] Ralph, J., "Hard Rock Miners Set to Plug Supply Gap," Commodities Research Unit (CRU), May 4, 2016. Retrieved from http://www.crugroup.com/about-cru/cruinsight/Hard_Rock_Miners_Set_to_Plug_Supply_Gap
[382] Stafford, J., "Tesla And Other Tech Giants Scramble For Lithium As Prices Double," OilPrice.com, April 12, 2016. Retrieved on May 5, 2016 from http://oilprice.com/Energy/Energy-General/Tesla-And-Other-Tech-Giants-Scramble-For-Lithium-As-Prices-Double.html.
[383] Stafford, J., " Why Lithium Will See Another Price Spike This Fall," OilPrice.com, July 18, 2016. Retrieved from http://oilprice.com/Energy/Energy-General/Why-Lithium-Will-See-Another-Price-Spike-This-Fall.html
[384] West, J., "Tesla Motors Inc ignites a lithium race among Albemarle, SQM and FMC," Financial Post, April 4, 2016. Retrieved on May 5, 2016 from http://business.financialpost.com/midas-letter/tesla-motors-inc-ignites-a-lithium-race-among-albemarle-sqm-and-fmc.
[385] Clarke, G. M., "Lithium Resource Availability - A Question of Demand," Proceedings 9th Advanced Automotive Battery Conference (AABC), June 12, 2009, Long Beach CA.
[386] Evans, K., "The Future of Electric Vehicles: Setting the Record Straight on Lithium Availability," Journal of Energy Security, August 27 2009.
[387] Carnegie Mellon University, "Lithium market fluctuations unlikely to significantly impact battery prices," Press Release, May 3, 2016. Retrieved on May 5, 2016 from https://engineering.cmu.edu/media/press/2016/05_03_lithium_market_fluctuations.html.
[388] U.S. EPA, "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy," EPA-420-R-12-901, August 2012.
[389] Spoken comments by Mark Reuss, Executive Vice President of Global Product Development, GM 2015 Global Business Conference, Oct 1 2015, slide 52 in 2015_GBC_Combined_PDF_v3.pdf. See Docket Memo "Transcript of Comments on Bolt EV Battery Cell Cost at GM 2015 Global Business Conference," EPA Docket EPA-HQ-OAR-2015-0827.
[390] General Motors, "General Motors 2015 Global Business Conference," Presentation, October 1, 2015, slide 52 in 2015_GBC_Combined_PDF_v3.pdf.
[391] Cole, J., "GM: Chevrolet Bolt Arrives In 2016, $145/kWh Cell Cost, Volt Margin Improves $3,500," InsideEVs.com, October 2, 2015. Retrieved from http://insideevs.com/gm-chevrolet-bolt-for-2016-145kwh-cell-cost-volt-margin-improves-3500/.
[392] Kalhammer, F. et al., "Status and Prospects for Zero Emissions Vehicle Technology - Report of the ARB Independent Expert Panel 2007," Sacramento, California, US: State of California Air Resources Board, 2007.
[393] U.S. Advanced Battery Consortium, "USABC Goals for Advanced Batteries for EVs - CY 2020 Commercialization," Downloaded on December 28, 2015 from http://www.uscar.org/commands/files_download.php?files_id=364.
[394] Tataria, H. and Lopez, H.A., "EV Battery Development (Envia Systems)," in Section III.A.1 p. 31 of "Fiscal Year 2013 Annual Progress Report for Energy Storage R&D," U.S. Department of Energy, DOE/EE-1038, February 2014.
[395] Keller, G., "DOE's Efforts to Develop Hybrid Powertrain technologies for Heavy-Duty Vehicles," SAE 2015 Hybrid & Electric Vehicle Technologies Symposium, February 12, 2015.
[396] Supplementary spreadsheet accompanying Nykvist, B. and Nilsson, M.; "Rapidly Falling Costs of Battery Packs for Electric Vehicles," Nature Climate Change, March 2015; doi: 10.1038/NCLIMATE2564, available at http://www.nature.com/nclimate/journal/v5/n4/extref/nclimate2564-s1.xlsx.

---

[397] Voelcker, J., "Nissan Leaf New Battery Cost: $5,500 For Replacement With Heat-Resistant Chemistry," Green Car Reports, June 28, 2014. Retrieved from http://www.greencarreports.com/news/1092983_nissan-leaf-battery-cost-5500-for-replacement-with-heat-resistant-chemistry.
[398] Brockman, B., "Update on Nissan LEAF Battery Replacement," MYNissanLeaf.com, June 27, 2014. Retrieved from http://www.mynissanleaf.com/viewtopic.php?f=4&t=17168.
[399] Cole, J., "Nissan Prices LEAF Battery Replacement at $5,499, New Packs More Heat Durable," InsideEVs.com, June 27, 2014. Retrieved from http://insideevs.com/breaking-nissan-prices-leaf-battery-replacement-5499-new-packs-heat-durable/.
[400] Voelcker, J., "Nissan Leaf $5,500 Battery Replacement Loses Money, Company Admits," Green Car Reports, July 24, 2014. Retrieved from http://www.greencarreports.com/news/1093463_nissan-leaf-5500-battery-replacement-loses-money-company-admits.
[401] Cobb, J., "How Long Will An Electric Car's Battery Last?" HybridCars.com, April 30, 2014. Retrieved from http://www.hybridcars.com/how-long-will-an-evs-battery-last/.
[402] NewGMParts.com. See http://stores.revolutionparts.com/newgmparts.com/chevrolet/volt/20979876/2011-year/base-trim/1-4l-l4-electric-gas-engine/electrical-cat/electrical-components-scat/?part_name=battery-assy
[403] InsideEVs.com, "BMW i3 Battery Module Costs $1,715.60 – 8 Modules Per Car – Total Cost $13,725," January 26, 2015. Retrieved from http://insideevs.com/bmw-i3-battery-module-costs-1715-60-8-modules-per-car-total-cost-13725/.
[404] Tesla Motors, "Roadster 3.0 Battery Upgrade," retrieved from http://shop.teslamotors.com/collections/roadster/products/roadster-3-0-upgrade.
[405] Ramsey, M., "Tesla Gets Boost From Korean Battery Maker LG Chem," The Wall Street Journal, October 28, 2015. Retrieved from http://www.wsj.com/articles/tesla-gets-boost-from-korean-battery-maker-lg-chem-1446007554.
[406] Smart USA, Battery Assurance Plus Brochure. Retrieved on May 6, 2016 from http://www.smartusa.com/resources/doc/smart_battery-assurance-plus_SEO.pdf.
[407] PluginCars.com, "Smart Electric Drive Review." Retrieved from http://www.plugincars.com/smart-ed
[408] White, J., "The Smart, a Very Cheap Electric Car With a Very Expensive Battery," The Wall Street Journal, August 7, 2013. Retrieved from http://blogs.wsj.com/corporate-intelligence/2013/08/07/the-smart-a-very-cheap-electric-car-with-a-very-expensive-battery/.
[409] Kane, M., "UK Pricing Reveals 30 kWh 2016 Nissan LEAF Costs Just £1,600 More Than 24 kWh Version," InsideEVs.com, September 14, 2015. Retrieved from http://insideevs.com/uk-pricing-reveals-30-kwh-2016-nissan-leaf-costs-just-1600-more-than-24-kwh-version/.
[410] Lux Research, "Tesla Motors' Gigafactory Will See More Than 50% Overcapacity in its Li-ion Production," Press Release, September 3, 2014. Retrieved from http://www.luxresearchinc.com/news-and-events/press-releases/read/tesla-motors%E2%80%99-gigafactory-will-see-more-50-overcapacity-its-li.
[411] National Research Council Canada, "Full-Scale Wind Tunnel Investigation of Light-Duty Vehicle Aerodynamics," NR AL-2014-0017, March 2014.
[412] Larose, G., Belluz, L., Whittal, I., Belzile, M. et al., "Evaluation of the Aerodynamics of Drag Reduction Technologies for Light-duty Vehicles: a Comprehensive Wind Tunnel Study," SAE Int. J. Passenger Cars - Mech. Syst. 9(2):2016, doi: 10.4271/2016-01-1613.
[413] National Research Council Canada "Evaluation of the aerodynamics of new drag reduction technologies for light-duty vehicles: results of Phase III" LTR-AL-2015-0061, February 23, 2016.
[414] U.S. EPA, "EPA Staff Informal Survey of Aerodynamic Technologies Represented at the 2015 North American International Auto Show (NAIAS)," memo to Docket EPA-HQ-OAR-2015-0827, May 16, 2016.
[415]Audi Technology Portal, http://www.audi-technology-portal.de/en/body/aerodynamics-aeroacoustics/underbody
[416] 2017 Prius, http://www.toyota.com/prius/ebrochure/.
[417] Arai, M., "Development of the Aerodynamics of the New Nissan Murano," Society of Automotive Engineering (SAE) Technical Paper #2015-01-1542, 2015.
[418] "2015 Nissan Murano- 10 Fast Facts", April 14, 2014, http://nissannews.com/en-CA/nissan/canada/channels/ca-canada-nissan-2014-NYIAS/releases/2015-nissan-murano-10-fast-facts.
[419] "Evaluation of the aerodynamics of new drag reduction technologies for light duty vehicles: Summary of Phases I to IV", National Research Council Canada and Transport Canada, December 2016.
[420] Madsen, A., "2015 Acura TLX Body Structure Review," Honda R&D Americas, Inc., 2015 Great Designs in Steel Conference, Livonia, MI, May 13, 2015.
[421] PR Newswire, "General Motors Commemorates 30 Years of Aerodynamic Progress," August 4, 2010.

[422] "Sophisticated Sophomore: All-New 2016 Chevrolet Cruze," GM Corporate Newsroom, June 24, 2015, http://media.chevrolet.com/media/us/en/gm/news.detail.print.html/content/Pages/news/us/en/2015/jun/0624-cruze.html.
[423] "How air curtains on F-150 help reduce aerodynamic drag and aid fuel efficiency", Ford Motor Company Media Center, July 15, 2015, https://media.ford.com/content/fordmedia/fna/us/en/news/2015/07/15/how-air-curtains-on-f-150-help-reduce-aerodynamic-drag.html.
[424] "How air curtains on F-150 help reduce aerodynamic drag and aid fuel efficiency", Ford Motor Company Media Center, July 15, 2015, https://media.ford.com/content/fordmedia/fna/us/en/news/2015/07/15/how-air-curtains-on-f-150-help-reduce-aerodynamic-drag.html.
[425] "Active Grille Shutters 2015 F-150, September 15, 2015, https://www.youtube.com/watch?v=23O-hS-r0gQ.
[426] "How Ford Squeezed Every Drop of Aerodyamics Out of the 2015 F150", August 26, 2014, http://truckyeah.jalopnik.com/how-a-boxy-truck-like-the-2015-ford-f-150-reduces-wind-1627125563.
[427] National Research Council Canada, "Evaluation of the aerodynamics of new drag reduction technologies for light-duty vehicles: results of Phase II," LTR-AL-2015-0273, Issued for Client's Comments, March 22, 2015.
[428] Chappell, L., "For mpg gains, tiremakers deliver - consumers shrug," Automotive News, December 1, 2014.
[429] Automotive World, "From radial to radical - where next for light vehicle tyres?," March 2015.
[430] Bridgestone, "Bridgestone's 'ologic technology' hits the road," Press Release, January 8, 2014. Retrieved on March 25, 2016 from http://www.bridgestone.eu/corporate/press-releases/2014/01/bridgestones-ologic-technology-hits-the-road/.
[431] Donley, T., "Improving Vehicle Fuel Efficiency Through Tire Design, Materials, and Reduced Weight," Cooper Tire & Rubber Co., presentation at 2014 DOE Annual Merit Review, Project VSS083.
[432] "Light Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2015, Executive Summary," U.S. EPA, EPA-420-S-15-001 December 2015, https://www.epa.gov/fuel-economy/trends-report..
[433] "GMC Introduces All-New 2017 Acadia," January 12, 2016, http://media.gmc.com/media/us/en/gmc/home.detail.html/content/Pages/news/us/en/2016/Jan/naias/gmc/0112-acadia.html.
[434] Chrysler's T&C minivan renamed "Pacifica," cuts 250 lbs. with steel, aluminum, magnesium," January 12, 2016, "http://www.repairerdrivennews.com/2016/01/12/chryslers-tc-minivan-renamed-pacifica-cuts-250-lbs-with-aluminum-steel-magnesium/.
[435] Ducker Worldwide, "2015 North American Light Vehicle Aluminum Content Study, Executive Summary," June 2014, http://www.drivealuminum.org/research-resources/PDF/Research/2014/2014-ducker-report.
[436] Composites Forecasts and Consulting, December 2015.
[437] Docket submittal of email from Abey Abraham of Ducker Worldwide to Cheryl Caffrey, 2/25/2016.
[438] Baron,J., PhD, "Assessing the Fleet-wide Material Technology and Costs to Lightweight Vehicles", Center for Automotive Research, September 2016, http://www.cargroup.org/?module=Publications&event=View&pubID=141
[439] "Alcoa's Micromill Technology for future cars", Aluminum Insider, 06 April 2016, http://aluminiuminsider.com/alcoas-micromill-technology-for-future-cars/.
[440] "GM says it's first to weld steel to aluminum", The Detroit News, May 20, 2016, http://www.detroitnews.com/story/business/autos/general-motors/2016/05/18/gm-says-first-weld-steel-aluminum/84558702/.
[441] U.S. EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2016," EPA-420-R-16-010, November 2016.
[442] http://www.freep.com/story/money/cars/mark-phelan/2015/06/24/2016-chevrolet-cruze-chevy-challenges/71265088/.
[443] http://www.worldautosteel.org/why-steel/steel-muscle-in-new-vehicles/2016-chevy-malibu-larger-lighter-more-efficient-with-hss/.
[444] "Cadillac XT5's new platform cuts weight- at less cost," SAE Automotive Engineering, April 2016.
[445] "The New Audi Q7- Sportiness, efficiency, premium comfort," December 12, 2014 https://www.audiusa.com/newsroom/news/press-releases/2014/12/the-new-audi-q7-sportiness-efficiency-premium-comfort.
[446] Mg Showcase Issue 12, International Magnesium Association, Spring 2010, http://www.intlmag.org/showcase/mgshowcase12_mar10.pdf.
[447] "Response to Peer Reviews for 'Light-Duty Truck Weight Reduction Study with Crash Model, Feasibility and Cost Analysis - Project Number: T8009-130016', September 24, 2015.

[448] "Light-Duty Vehicle Mass Reduction and Cost Analysis --Midsize Crossover Utility Vehicle", EPA-420-R-12-026, August 2012.
[449] General Motors, "General Motors 2015 Global Business Conference," Presentation, October 1, 2015, Slides 43-45 in document, https://www.gm.com/content/dam/gm/events/docs/5194074-596155-ChartSet-10-1-2015.
[450] "Identifying Real World Barriers to Implementing Lightweighting Technologies and Challenges in Estimating the Increase in Costs," Center for Automotive Research, Jay Baron, PhD, January 2016 http://www.cargroup.org/?module=Publications&event=View&pubID=128.
[451] "Mass Reduction and Cost Analysis - Light Duty Pickup Truck Model years 2020-2025, FEV North America, Inc., EPA-420-R-15-006, June 2015. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100MS0E.PDF?Dockey=P100MS0E.PDF .
[452] "Evaluating the Structure and Crashworthiness of a 2020 Model-year, Mass Reduced Crossover Vehicle using FEA Modeling," California Air Resources Board and Lotus Engineering, August 31, 2012.
[453] "An Assessment of Mass Reduction Opportunities for a 2017 – 2020 Model Year Vehicle Program," Lotus Engineering, Inc. for ICCT, March 2010.
[454] "Venza Aluminum BIW Concept Study," April 2013, http://www.drivealuminum.org/research-resources/PDF/Research/2013/venza-biw-full-study.
[455] Conklin, J., Beals, R., and Brown, Z., "BIW Design and CAE," SAE Technical paper 2015-01-0408, 2015, doi:10.4271/2015-01-0408.
[456] "Evaluating the Structure and Crashworthiness of a 2020 Model-Year, Mass-Reduced Crossover Vehicle Using FEA Modeling," Lotus Engineering for California Air Resources Board, August 31, 2012. https://www.epa.gov/air-pollution-transportation/evaluating-structure-and-crashworthiness-2020-model-year-mass-reduced
[457] "Venza Aluminum BIW Concept Study," April 2013, http://www.drivealuminum.org/research-resources/PDF/Research/2013/venza-biw-full-study.
[458] Source: Kelkar et al: "Automobile Bodies: Can Aluminum Be an Economical Alternative to Steel?," August 2001 Issue of JOM., 53 (8) (2001)pp. 28-32, http://www.tms.org/pubs/journals/JOM/0108/Kelkar-0108.html.
[459] " http://energy.gov/sites/prod/files/2015/12/f27/06%20-%20Lightweight%20Materials.pdf.
[460] Skszek, T., Conklin, J, Zaluzec, M, Wagner, D.,"Multi-Material Lightweight Vehicles: Mach-II Design," U.S. DOE, Ford, Vehma, June 17, 2014, http://energy.gov/sites/prod/files/2014/07/f17/lm088_skszek_2014_o.pdf.
[461] Mascarin,A., Hannibal,T., Raghunathan, A., Ivanic, Z., Francfort, J., "Vehicle Lightweighting: 40% and 45% Weight Savings Analysis: Technical Cost Modeling for Vehicle Lightweighting," INL/EXT-14-33863, April 2015, http://avt.inl.gov/pdf/TechnicalCostModel40and45PercentWeightSavings.pdf.
[462] Skszek, T., Zaluzec, M., Conklin, J., and Wagner D., "MMLV: Project Overview," SAE Technical Paper 2015-01-0407, 2015 doi: 10.4271/2015-01-0407.
[463] Bolar, N., Buchler, T., Li, A., and Wallace, J., "MMLV: Vehicle Durability Design, Simulation and Testing," SAE Technical Paper 2015-01-1613, 2015, doi: 10.4271/2015-01-1613.
[464] Bushi, L., Skszek, T., and Wagner, D., "MMLV: Life Cycle Assessment," SAE Technical Paper 2015-01-1616, 2015, doi: 10.4271/2015-01-1616.
[465] Chen, X., Conklin, J., Carpenter, R., Wallace, J. et al., "MMLV: Chassis Design and Component Testing," SAE Technical Paper 2015-01-1237, 2015, doi: 10.4271/2015-01-1237.
[466] Chen, Y., Board, D., Faruque, O., Stancato, C. et al, "MMLV: Crash Safety Performance," SAE Technical Paper 2015-01-1614, 2015, doi: 10.4271/2015-01-1614.
[467] Conklin, L., Beals, R., and Brown, Z., "BIW Design and CAE," SAE Technical Paper 2015-01-0408, 2015, doi: 104271/2015-01-0408.
[468] Corey, N., Madin, M., and Williams, R., "MMLV: Carbon Fiber Composite Engine Parts," SAE Technical Paper 2015-01-1239, doi: 10.4271/2015-01-1239.
[469] Gur, Y., Pan, J., Huber, J., and Wallace, J., "MMLV: NVH Sound Package Development and Full Vehicle Testing," SAE Technical Paper 2015-01-1615, 2015, doi: 10.4271/2015-01-1615.
[470] Jaranson, J., and Ahmed, M., "MMLV: Lightweight Interior Systems Design," SAE Technical Paper 2015-01-1236, 2015, doi: 10.4271/2015-01-1236.
[471] Kearns, J., Park, S., Sabo, J., and Milacic, D., "MMLV: Automatic Transmission Lightweighting," SAE Technical Paper 2015-01-1240, 2015, doi: 10.4271/2015-01-1240.
[472] Maki, C., Byrd, K., McKeough, B., Rentschler, R. et al., "MMLV: Aluminum Cylinder Block with Bulkhead Inserts and Aluminum Alloy Connecting Rod," SAE Technical Paper 2015-01-1238, 2015, doi: 10.4271/2015-01-1238.
[473] Plourde, L., Azzouz, M., Wallace, J., and Chellman, M., "MMLV: Door Design and Component Testing," SAE Technical Paper 2015-01-0409, 2015, doi: 10.4271/2015-01-0409.

[474] Schutte, C., "DOE Focuses on Developing Materials to Improve Vehicle Efficiency," SAE Technical Paper 2015-01-0405, 2015, doi: 10.4271/2015-01-0405.
[475] Skszek,T., Conklin, J., Wagner, D., Zaluzec.M., "Multi-Material Lightweight Vehicles," Ford Motor Company and Vehma International, June 11, 2015, presented at 2015 DOE AMR, http://energy.gov/sites/prod/files/2015/06/f24/lm072_skszek_2015_o.pdf.
[476] IBIS Associates, Inc., "Technical Cost Modeling for Vehicle Lightweighting: 40% and 45% Weight Reduction," June 11, 2015, http://energy.gov/sites/prod/files/2015/06/f24/lm090_mascarin_2015_o.pdf.
[477] Chapter 6 Lightweight Materials within the "Vehicle Technologies Office: 2015 Annual Merit Review Report" http://energy.gov/sites/prod/files/2015/12/f27/06%20-%20Lightweight%20Materials.pdf.
[478] IBIS Associates, Energetics Incorporated, Idaho National Laboratory, "Vehicle Lightweighting: Mass Reduction Spectrum analysis and Process Cost Modeling Project ID #LM090", June 7, 2016, http://energy.gov/sites/prod/files/2016/06/f33/lm090_mascarin_2016_o_web.pdf.
[479] "Update to Future Midsize Lightweight Vehicle Findings in Response to Manufacturer Review and IIHS Small Overlap Testing," NHTSA, DOT HS 812 237, February 2016. http://www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf.
[480] "Light-Duty Truck Weight Reduction Study with Crash Model, Feasibility and Cost Analysis," T8009-130016, Department of Transport Canada, September 24, 2015.
[481] "Novel Malleable Covalent Networks and Their applications in Repairable Carbon Fiber Reinforced Composites with Full Recyclability", Wei Zhang, Department of Chemistry and biochemistry at the University of Colorado, Boulder, Global Automotive Lightweight Materials Conference, August 23-25, 2016, Detroit.
[482] MALLINDA Reshaping the Plastics Industry, https://mallinda.squarespace.com/about/.
[483] "Mallinda awarded $750k grant for resusable carbon-fiber composite", October 12, 2016, http://www.colorado.edu/nvc/2016/10/12/mallinda-awarded-750k-grant-reusable-carbon-fiber-composite.
[484] http://www.cyclotronroad.org/.
[485] "ORNL seeking U.S. manufacturers to license low-cost carbon fiber process", March 22 2016, https://www.ornl.gov/news/ornl-seeking-us-manufacturers-license-low-cost-carbon-fiber-process.
[486] "ORNL seeking U.S. manufacturers to license low-cost carbon fiber process", March 22 2016, https://www.ornl.gov/news/ornl-seeking-us-manufacturers-license-low-cost-carbon-fiber-process.
[487] Brooke, L. "Systems Engineering a new 4x4 benchmark," SAE Automotive Engineering, June 2, 2014
[488] Phelps, P., "EcoTrac Disconnecting AWD System," presented at 7th International CTI Symposium North America 2013, Rochester MI.
[489] Pilot Systems, "AWD Component Analysis," Project Report, performed for Transport Canada, Contract T8080-150132, May 31, 2016.
[490] Martin, B. et al., "The Innovative driveline of the 9-Speed Jeep Cherokee," presented at 8th International CTI NA Symposium, May 2014, Rochester, MI.
[491] Lee, B., "A Novel Clutch Solution for AWD Disconnect," presented at 9th International CTI Symposium North America 2015, Rochester, MI.
[492] U.S. Environmental Protection Agency, Greenhouse Gas Emission Standards for Light Duty Vehicles, Manufacturer Performance Report for the 2014 Model Year, EPA-420-R-15-026, December 2015.
[493] U.S. Environmental Protection Agency, Greenhouse Gas Emission Standards for Light Duty Vehicles, Manufacturer Performance Report for the 2015 Model Year, EPA-420-R-16-014, November 2016.
[494] General Motors, "Request for GHG Credit for Variable Crankcase Suction Valve Technology ," Letter to Linc Wehrly, December 9, 2014. Available at https://www.epa.gov/sites/production/files/2016-09/documents/gm-sas-compressor-off-cycle-credit-petition-fe6349-2014-12-09.pdf.
[495] U.S. EPA, "EPA Decision Document: Off-cycle Credits for Fiat Chrysler Automobiles, Ford Motor Company, and General Motors Corporation," EPA-420-R-15-014, September 2015. Available at https://nepis.epa.gov/Exe/ZyPDF.cgi/P100N19E.PDF?Dockey=P100N19E.PDF.
[496] Sciance, F. et al., "Developing the AC17 Efficiency Test for Mobile Air Conditioners," SAE Technical Paper 2013-01-0569, April 2013.
[497] See Greenhouse Gas Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2015 Model Year, EPA-420-R-16-014, November 2016.
[498] Minnesota Pollution Control Agency, Mobile Air Conditioner Leakage Rates, www.pca.state.mn.us.
[499] http://www.greencarcongress.com/2015/10/20151020-mbco2.html.
[500] Andersen et al., 2015. "Secondary Loop Motor Vehicle Air Conditioning Systems (SL---MACs). Using Low-Global Warming Potential (GWP) Refrigerants in Leak-Tight Systems In Climates with High Fuel Prices and Long,

Hot and Humid Cooling Seasons. Building on the Previous Success of Delphi, Fiat, General Motors, Volvo, Red Dot, SAE Cooperative Research Projects, And Other Engineering Groups." MACS Briefing, 2015.
501 77 FR 62832, October 15, 2012.
502 77 FR 62835-62837.
503 77 FR 62835-62836.
504 40 CFR 86.1869-12.
505 40 CFR 86.1869-12(b).
506 40 CFR 86.1869-12(c).
507 40 CFR 86.1869-12(d).
508 For a description of each technology and the derivation of the pre-defined credit levels see Chapter 5 of "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy," EPA-420-R-12-901, August 2012.
509 40 CFR 86.1869-12 (b)(4).
510 U.S. Environmental Protection Agency, Greenhouse Gas Emission Standards for Light Duty Vehicles, Manufacturer Performance Report for the 2015 Model Year, EPA-420-R-16-014, November 2016.
511 "EPA Decision Document: Mercedes-Benz Off-cycle Credits for MYs 2012-2016," U.S. EPA-420-R-14-025, Office of Transportation and Air Quality, September 2014. See http://www.epa.gov/otaq/regs/ld-hwy/greenhouse/documents/420r14025.pdf.
512 "EPA Decision Document: Off-cycle Credits for Fiat Chrysler Automobiles, Ford Motor Company, and General Motors Corporation," U.S. EPA-420-R-15-014, Office of Transportation and Air Quality, September 2015. See https://www.epa.gov/vehicle-and-engine-certification/compliance-information-light-duty-greenhouse-gas-ghg-standards
513 Alternative Method for Calculating Off-cycle Credits Under the Light-Duty Vehicle Greenhouse Gas Emissions Program: Applications from BMW Group, Ford Motor Company, General Motors Corporation, and Volkswagen Group of America, Federal Register 81 (2 September 2016): 60694.
514 National Academy of Sciences. 2011. *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*. National Academies Press, ISBN 978-0-309-15607-3, http://www.nap.edu/catalog.php?record_id=12924, p.25
515 NAS, 2011, p. 62 footnote.
516 National Academy of Sciences. 2015. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. National Academies Press, ISBN 978-0-309-37388-3, http://www.nap.edu/21744, p.281.
517 NAS, 2011, p. 46.
518 Energy and Environmental Analysis, Inc. 2007. *Update for Advanced Technologies to Improve Fuel Economy of Light Duty Vehicles*. Prepared for U.S. Department of Energy. August. Arlington, Va (EPA-HQ-OAR-2014-0827-0722).
519 NAS, 2011, p. 62 footnote.
520 http://www.fordservicecontent.com/Ford_Content/Catalog/owner_information/2017-F-150-Owners-Manual-version-1_om_EN-US_08_2016.pdf.
521 https://iaspub.epa.gov/otaqpub/.
522 National Academies of Sciences. "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," The National Academies Press, 2015 (EPA-HQ-OAR-2015-0827-DRAFT-0398).
523 National Academy of Sciences. "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," The National Academies Press, 2015 (EPA-HQ-OAR-2015-0827-DRAFT-0398).
524 https://www3.epa.gov/otaq/climate/mte.htm#epa-publications.
525 Nelson, P.A. Gallagher, K.G., Bloom, I., and Dees, D.W., "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric Drive Vehicles," Second Edition, Argonne National Laboratory, ANL-12/55 (December 2012).
526 Gallagher, K., Shabbir, A., Nelson, P., and Dees, D., "PHEV and EV Battery Performance and Cost Assessment," Argonne National Laboratory, presented at the 2015 U.S. DOE Vehicle Technologies Office Annual Merit Review and Peer Evaluation, June 9, 2015.
527 Cite to EPA report containing our Executive Summary followed by the final learning report from ICF.
528 "Learning Curves used in Developing Technology Costs in the Draft TAR," Memorandum from Todd Sherwood to Air Docket EPA-HQ-OAR_2015-0827, June 8, 2016.
529 "Learning Curves used in Developing Technology Costs in the Draft TAR," Memorandum from Todd Sherwood to Air Docket EPA-HQ-OAR_2015-0827, June 8, 2016.
530 RTI International, "Automobile Industry Retail Price Equivalent and Indirect Cost Multipliers," February 2009; EPA-420-R-09-003; http://www.epa.gov/otaq/ld-hwy/420r09003.pdf.

---

531 Rogozhin, A., et al., "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry," International Journal of Production Economics (2009), doi:10.1016/j.ijpe.2009.11.031.
532 Rogozhin, A., et. al., "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry," International Journal of Production Economics (2009); "Documentation of the Development of Indirect Cost Multipliers for Three Automotive Technologies," Helfand, G., and Sherwood, T., Memorandum dated August 2009; "Heavy Duty Truck Retail Price Equivalent and Indirect Cost Multipliers," Draft Report prepared by RTI International and Transportation Research Institute, University of Michigan, July 2010.
533 Vyas, A., D. Santini and R. Cuenca; "Comparison of indirect Cost Multipliers for Vehicle Manufacturing;" April 2000.
534 "Joint Technical Support Document: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards," EPA-420-R-12-901, August 2012.
535 National Academy of Sciences. "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," The National Academies Press, 2015 (EPA-HQ-OAR-2015-0827-DRAFT-0398).
536 See https://www.epa.gov/otaq/climate/mte.htm.
537 See https://www.epa.gov/otaq/climate/data-testing.htm.
538 Newman, K., Kargul, J., and Barba, D., "Benchmarking and Modeling of a Conventional Mid-Size Car Using ALPHA," SAE Technical Paper 2015-01-1140, 2015, doi:10.4271/2015-01-1140.
539 Novation Analytics, *Technology Effectiveness – Phase II: Vehicle-Level Assessment*, version 1.0, prepared for Alliance of Automobile Manufacturers & Association of Global Automakers, September 20, 2016, p. 44.
540 Novation Analytics, *Technology Effectiveness – Phase I: Fleet-Level Assessment*, version 1.1, prepared for Alliance of Automobile Manufacturers & Association of Global Automakers, October 19, 2015, p. 58.
541 EPA-HQ-OAR-2015-0827-0899.
542 See https://www.epa.gov/otaq/climate/alpha.htm.
543 Newman, K., Kargul, J., and Barba, D., "Development and Testing of an Automatic Transmission Shift Schedule Algorithm for Vehicle Simulation," SAE Int. J. Engines 8(3):1417-1427, 2015, doi:10.4271/2015-01-1142.
544 Lee, S., Lee, B., McDonald, J. and Nam, E., "Modeling and Validation of Lithium-Ion Automotive Battery Packs," SAE Technical Paper 2013-01-1539, 2013, doi:10.4271/2013-01-1539.
545 Lee, S., Cherry, J., Lee, B., McDonald, J., Safoutin, M., "HIL Development and Validation of Lithium Ion Battery Packs," SAE Technical Paper 2014-01-1863, 2014, doi:10.4271/2014-01-1863.
546 Newman, K., Doorlag, M., and Barba, D., "Modeling of a Conventional Mid-Size Car with CVT Using ALPHA and Comparable Powertrain Technologies," SAE Technical Paper 2016-01-1141, 2016, doi:10.4271/2016-01-1141.
547 Novak, J. and Blumberg, P., "Parametric Simulation of Significant Design and Operating Alternatives Affecting the Fuel Economy and Emissions of Spark-Ignited Engines," SAE Technical Paper 780943, 1978, doi:10.4271/780943.
548 Heywood, J. B.,1988, *Internal Combustion Engine Fundamentals*, McGraw Hill, ISBN 007028637, p. 676.
549 Patton, K., Nitschke, R., and Heywood, J., "Development and Evaluation of a Friction Model for Spark-Ignition Engines," SAE Technical Paper 890836, 1989, doi:10.4271/890836.
550 Sandoval, D. and Heywood, J., "An Improved Friction Model for Spark-Ignition Engines," SAE Technical Paper 2003-01-0725, 2003, doi:10.4271/2003-01-0725.
551 EPA Test Car List data files, https://www.epa.gov/compliance-and-fuel-economy-data/data-cars-used-testing-fuel-economy Accessed April 11, 2016.
552 Argonne National Labs Downloadable Dynamometer Database, http://www.anl.gov/energy-systems/group/downloadable-dynamometer-database/conventional-vehicles Accessed April 12, 2016.
553 Baldauf, R.W., Devlin, R.B., Gehr, P., Giannelli, R., Hassett-Sipple, B., Jung, H., Martini, G., McDonald, J., Sacks, J.D., Walker, K. "Ultrafine Particle Metrics and Research Considerations: Review of the 2015 UFP Workshop." International Journal of Environmental Research and Public Health, 2016.
554 Lee, S., Schenk, C., and McDonald, J., "Air Flow Optimization and Calibration in High-Compression-Ratio Naturally Aspirated SI Engines with Cooled-EGR," SAE Technical Paper 2016-01-0565, 2016, doi: 10.4271/2016-01-0565.
555 Ellies, B., Schenk, C., and Dekraker, P., "Benchmarking and Hardware-in-the-Loop Operation of a 2014 MAZDA SkyActiv 2.0L 13:1 Compression Ratio Engine," SAE Technical Paper 2016-01-1007, 2016, doi:10.4271/2016-01-1007.
556 Kargul, J., Moskalik, A., Barba, D., Newman, K. et al., "Estimating GHG Reduction from Combinations of Current Best-Available and Future Powertrain and Vehicle Technologies for a Midsized Car Using EPA's ALPHA Model," SAE Technical Paper 2016-01-0910, 2016, doi:10.4271/2016-01-0910.

[557] Patton, et al. “Aggregating Technologies for reduced Fuel Consumption: A Review of the Technical Content in the 2002 National Research Council Report on café.” SAE 2002-01-0628. Society of Automotive Engineers, 2002.
[558] National Academy of Sciences. 2015. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. National Academies Press, ISBN 978-0-309-37388-3, http://www.nap.edu/21744, p.2.
[559] Wilcutts, M., Switkes, J., Shost, M., and Tripathi, A., "Design and Benefits of Dynamic Skip Fire Strategies for Cylinder Deactivated Engines," SAE Int. J. Engines 6(1):278-288, 2013, doi:10.4271/2013-01-0359.
[560] Schamel, A., Scheidt, M., Weber, C. Faust, H. Is Cylinder Deactivation a Viable Option for a Downsized 3-Cylinder Engine? Vienna Motor Symposium, 2015.
[561] Hitomi, M. "Our Direction for ICE (Internal Combustion Engine) - Consideration of Engine Displacement." Vienna Motor Symposium, 2015.
[562] Hitomi, M. "Mazda's Approach for Developing Engines from a Perspectiv of Environmental Improvement." Presentation at the 2015 ERC Symposium. Last accessed on the Internet on 11/20/2016 at the following URL: https://www.erc.wisc.edu/documents/symp15/2015_Mazda_-_Hitomi_-Apprd_revised.pdf.
[563] Tisshaw, M. " Next-generation Mazda engines to eclipse electric cars on emissions." Autocar, March 2014. Last accessed on the Internet on 11/20/2016 at the following URL: http://www.autocar.co.uk/car-news/industry/next-generation-mazda-engines-eclipse-electric-cars-emissions.
[564] Fletcher, G. " Future iterations of Mazda's trademark technology will further refine the internal combustion engine." Driving, June 2014. Last accessed on the Internet on 11/20/2016 at the following URL: http://driving.ca/mazda/auto-news/news/mazdas-skyactiv-looks-to-wring-out-more-efficiency.
[565] Stuhldreher, M., "Fuel Efficiency Mapping of a 2014 6-Cylinder GM EcoTec 4.3L Engine with Cylinder Deactivation," SAE Technical Paper 2016-01-0662, 2016, doi:10.4271/2016-01-0662.
SAE Technical Paper 2016-01-0662, 2016, doi:10.4271/2016-01-0662.
[566] Schamel, A., Scheidt, M., Weber, C. Faust, H. "Is Cylinder Deactivation a Viable Option for a Downsized 3-Cylinder Engine?" Vienna Motor Symposium, 2015.
[567] Alger, T., Gingrich, J., Mangold, B., and Roberts, C., "A Continuous Discharge Ignition System for EGR Limit Extension in SI Engines," SAE Int. J. Engines 4(1):677-692, 2011, doi:10.4271/2011-01-0661.
[568] Alger, T., Mangold, B., Roberts, C., and Gingrich, J., "The Interaction of Fuel Anti-Knock Index and Cooled EGR on Engine Performance and Efficiency," SAE Int. J. Engines 5(3):1229-1241, 2012, doi:10.4271/2012-01-1149.
[569] Sasaki, Y., Adachi, S., Nakata, K., Tanei, K., Shibuya, S. "The new Toyota 1.0L L3 ESTEC gasoline engine." 35th International Vienna Motor Symposium, 2014.
[570] Alt, M.; Sutter, T., Johnen, T., Fulton, K., Daily, R., Cococcetta, R., K., Peralta, N., Damen, M., O’Daniel, G., Noe, A., Krischker, U. " Powerful, efficient and smooth: The new Small Gasoline Engine family from General Motors." 35th International Vienna Motor Symposium, 2014.
[571]Hwang, K., Hwang, I., Lee, H., Park, H. et al., "Development of New High-Efficiency Kappa 1.6L GDI Engine," SAE Technical Paper 2016-01-0667, 2016, doi:10.4271/2016-01-0667.
[572] Aiyoshizawa, E., Hori., K. "The New Nissan High Efficient 4-Cylinder 1.6L GDI turbocharged engine with low pressure EGR - Evolution for Lower Fuel Consumption combined with High Output Performance." 35th International Vienna Motor Symposium, 2014.
[573] Glahn, C. Kluin, M. Königstein, A., Cloos, L. "Cooled External EGR – System Optimization of the Cooling and Charging System on a 3-Cylinder Gasoline DI T/C Engine." 24th Aachen Colloquium Automobile and Engine Technology 2015.
[574] See Docket EPA-HQ-OAR-2015-0827, Docket item titled “Air Flow Optimization and Calibration in High-Compression-Ratio Naturally Aspirated SI Engines with Cooled EGR.”
[575] EPA, "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2015," EPA-420-R-15-016, December 2015.
[576] Cruff, L., Kaiser, M., Krause, S., Harris, R. et al., "EBDI® - Application of a Fully Flexible High BMEP Downsized Spark Ignited Engine," SAE Technical Paper 2010-01-0587, 2010, doi:10.4271/2010-01-0587.
[577] Kaiser, M., Krueger, U., Harris, R., and Cruff, L., "“Doing More with Less” - The Fuel Economy Benefits of Cooled EGR on a Direct Injected Spark Ignited Boosted Engine," SAE Technical Paper 2010-01-0589, 2010, doi:10.4271/2010-01-0589.
[578] King, J., Heaney, M. Saward, J., Fraser, A., Criddle, M. Cheng, T., Morris, G., Bloore, P. “HyBoost: An Intelligently Electrified Optimised Downsized Gasoline Engine Concep.t’ SAE-China and FISITA (eds.), Proceedings of the FISITA 2012 World Automotive Congress, Lecture Notes in Electrical Engineering 191, DOI: 10.1007/978-3-642-33777-2_39.

[579] King, J., Böcker, O. "Multiple Injection and Boosting Benefits for Improved Fuel Consumption on a Spray Guided Direct Injection Gasoline Engine." SAE-China and FISITA (eds.), Proceedings of the FISITA 2012 World Automotive Congress, Lecture Notes in Electrical Engineering 189, DOI: 10.1007/978-3-642-33841-0_18.
[580] Brooke, L. "Ricardo begins EBDI V6 road test program." SAE Automotive Engineering, February 2010. Last accessed on the Internet on 11/11/2016 at the following URL: http:// http://articles.sae.org/7656/.
[581] Wada, Y., Nakano, K., Mochizuki, K., and Hata, R., "Development of a New 1.5L I4 Turbocharged Gasoline Direct Injection Engine," SAE Technical Paper 2016-01-1020, 2016, doi:10.4271/2016-01-1020.
[582] Nakano, K., Wada, Y., Jono, M., Narihiro, S. "New In-Line 4-Cylinder Gasoline Direct Injection Turbocharged Downsizing Engine." Honda R&D Technical Review, April 2016, pp 139-146.
[583] Budack, R., Kuhn, M., Wurms, R., Heiduk, T., "Optimization of the Combustion Process as Demonstrated on the New Audi 2.0l TFSI," 24th Aachen Colloquium Automobile and Engine Technology 2015.
[584] Wurms, R., Budack, R., Grigo, M., Mendl, G., Heiduk, T., Knirsch, S. "The new Audi 2.0l Engine with innovative Rightsizing," 36. Internationales Wiener Motorensymposium 2015.
[585] Eichler, F., Demmelbauer-Ebner, W., Theobald, J., Stiebels, B., Hoffmeyer, H., Kreft, M. "The New EA211 TSI® evo from Volkswagen." 37. Internationales Wiener Motorensymposium 2016.
[586] "National Academy of Sciences. " 2015. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles." ISBN 978-0-309-37388-3 p. 5-52 (Finding 5.3) http://www.nap.edu/catalog.php?record_id=21744.
[587] Moskalik, A., Hula, A., Barba, D., and Kargul, J., "Investigating the Effect of Advanced Automatic Transmissions on Fuel Consumption Using Vehicle Testing and Modeling," *SAE Int. J. Engines* 9(3):1916-1928, 2016, doi:10.4271/2016-01-1142.
[588] *EPA ALPHA Samples Transmission Walk*, David Oh, Will Ruona, Greg Goleski, Ford Motor CO., 9/2016, included as Attachment 8 of the AAM comments.
[589] National Academies of Science. 2011. *Assessment of Fuel Economy Technologies for Light-Duty Vehicles*. National Academies Press, ISBN 978-0-309-15607-3, http://www.nap.edu/catalog.php?record_id=12924, p.25.
[590] Moskalik, A., Hula, A., Barba, D., and Kargul, J., "Investigating the Effect of Advanced Automatic Transmissions on Fuel Consumption Using Vehicle Testing and Modeling," *SAE Int. J. Engines* 9(3):1916-1928, 2016, doi:10.4271/2016-01-1142.
[591] Greiner, J., Grumbach, M., Dick, A., and Sasse, C., "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE Technical Paper 2015-01-1087, 2015, doi:10.4271/2015-01-1087.
[592] Greiner, J., Grumbach, M., Dick, A., and Sasse, C., "Advancement in NVH- and Fuel-Saving Transmission and Driveline Technologies," SAE Technical Paper 2015-01-1087, 2015, doi:10.4271/2015-01-1087.

[594] Wayland, M., "Hyundai: Ioniq Hybrid achieves 58 mpg," The Detroit News, November 10, 2016. Retrieved from http://www.detroitnews.com/story/business/autos/foreign/2016/11/10/hyundai-ioniq-hybrid-achieves-mpg/93618350/
[595] Bunkley, N., "Ford plans EV to compete with Chevy Bolt, Tesla Model 3, Fields confirms," Automotive News, April 28, 2016. Retrieved on November 2, 2016 from http://www.autonews.com/article/20160428/OEM05/160429821/fields-confirms-ford-planning-ev-to-compete-with-chevy-bolt-tesla.
[596] Nikkei Asian Review, "Toyota to mass produce electric vehicles," November 7, 2016. Retrieved on November 7, 2016 from http://asia.nikkei.com/Japan-Update/Toyota-to-mass-produce-electric-vehicles.
[597] Tajitsu, N. et al., "Toyota, in about-face, may mass-produce long-range electric cars: Nikkei," November 7, 2016. Retrieved on November 7, 2016 from http://www.reuters.com/article/us-toyota-electric-cars-idUSKBN13204D.
[598] Hall, L., "2017 Renault Zoe Getting New 200-Mile Battery - Nissan Leaf to Follow?," HybridCars.com, September 28, 2016. Retrieved from http://www.hybridcars.com/2017-renault-zoe-getting-new-200-mile-battery-nissan-leaf-to-follow/.
[599] California Air Resources Board, "Request for Proposal 15CAR018, Advanced Strong Hybrid and Plug-In Hybrid Engineering Evaluation and Cost Analysis," May 9, 2016.
[600] Nelson, P.A. Gallagher, K.G., Bloom, I., and Dees, D.W., "Modeling the Performance and Cost of Lithium-Ion Batteries for Electric Drive Vehicles," Second Edition, Argonne National Laboratory, ANL-12/55 (December 2012).
[601] See EPA Docket EPA-HQ-OAR-2015-0827, Docket item titled "Instructions for Accessing EPA Battery Analysis (Proposed Determination)."
[602] International Energy Agency (IEA), Global EV Outlook 2016 (Flyer). Retrieved from http://www.iea.org/media/topics/transport/GlobalEVOutlook2016FLYER.pdf.

[603] International Energy Agency (IEA), Global EV Outlook 2016: Beyond one million electric cars. Retrieved from http://www.iea.org/publications/freepublications/publication/global-ev-outlook-2016.html.
[604] Plumer, B., "The rapid growth of electric cars worldwide, in 4 charts," Vox, June 6, 2016. Retrieved on November 4, 2016 from http://www.vox.com/2016/6/6/11867894/electric-cars-global-sales.
[605] See 40 CFR 600.116-12(a)(6), 40 CFR 600.210-12(d)(3), and 76 FR 39478.
[606] See http://www.uscar.org/guest/partnership/1/us-drive.
[607] US DRIVE Partnership, "US DRIVE Electrical and Electronics Technical Team Roadmap," June 2013. downloaded on Dec. 23, 2015 from http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap_june2013.pdf.
[608] Slenzak, J., "Next Generation Electrification Products: Focus on Integration and Cost Reduction," Bosch, The Battery Show 2015, Novi MI, September 15, 2015.
[609] cf. U.S. DRIVE Electrical and Electronics Technical Team Roadmap, p 10.
[610] Gardner, G., "The self-driving revolution will be mostly electric," Detroit Free Press, September 21, 2106. Retrieved from http://www.freep.com/story/money/cars/2016/09/18/self-driving-revolution-mostly-electric/90410520/.
[611] Anandan, V., "Current Status of Solid State Batteries for Automotive Applications," The Battery Show 2016, Novi, MI, September 14, 2016.
[612] Farid, A., "Battery adoption at tipping point - identifying investment opportunities," Berenberg, The Battery Show Conference and Electric & Hybrid Vehicle Technology Conference, September 13, 2016.
[613] Safoutin, M., "EPA Battery Sizing and Cost Analysis for Future Plug-in Vehicles for the Midterm Evaluation of the 2022-2025 Light-Duty GHG Standards," The Battery Show Conference and Electric & Hybrid Vehicle Technology Conference, September 15, 2016.
[614] General Motors Press Release, "Drive Unit and Battery at the Heart of Chevrolet Bolt EV," January 11, 2016, downloaded on Jan. 21, 2016 from http://media.chevrolet.com/media/us/en/chevrolet/home.detail.html/content/Pages/news/us/en/2016/Jan/naias/chevy/0111-bolt-du.html.
[615] Anderman, M., "Battery Packs of Modern xEVs: A Comprehensive Engineering Assessment: Extract," Total Battery Consulting, 2016, slides 19 and 30.
[616] See EPA Docket EPA-HQ-OAR-2015-0827, Microsoft Excel attachment to Docket Item titled "Data and Charts for Selected Figures in Electrification Chapters of Proposed Determination TSD."
[617] Nelson, P.A., Santini, D.J., Barnes, J. "Factors Determining the Manufacturing Costs of Lithium-Ion Batteries for PHEVs," 24th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition EVS-24, Stavenger, Norway, May 13-16, 2009 (www.evs24.org).
[618] Santini, D.J., Gallagher, K.G., and Nelson, P.A. "Modeling of Manufacturing Costs of Lithium-Ion Batteries for HEVs, PHEVs, and EVs," Paper to be presented at the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exposition, EVS-25, Shenzhen, China, November 5-9, 2010 (www.evs25.org). Advance draft provided by D.J. Santini, Argonne National Laboratory, August 24, 2010.
[619] See Docket item EPA-HQ-OAR-2010-0799-11913.
[620] ICF International, Peer Review Report of the Draft Report "Modeling the Cost and Performance of Lithium-Ion Batteries for Electric-Drive Vehicles," March 31, 2011. See Docket item EPA-HQ-OAR-2010-0799-1080.
[621] See Docket items EPA-HQ-OAR-2010-0799-1078 and EPA-HQ-OAR-2010-0799- 11914.
[622] Argonne National Laboratory, "Changes to BatPaC for Version 3.0," available at http://www.cse.anl.gov/batpac/files/Changes%20to%20BatPaC%20for%20Version%203%2021Dec2015.pdf.
[623] Argonne National Laboratory, "BatPaC (Battery Performance and Cost)," BatPaC Version 3.0 Beta 17Dec2015.xlsx. A copy is available in Docket EPA-HQ-OAR-2015-0827.
[624] Anderman, M., "Battery Packs of Modern xEVs: A Comprehensive Engineering Assessment: Extract," Total Battery Consulting, 2016, slide 52.
[625] "AWD Component Analysis," Pilot Systems for Transport Canada, 2016.

Table of Contents

Table of Figures

Table of Tables

Chapter 3: Economic and Other Key Inputs Used in EPA's Analyses

3.1 The On-Road Fuel Economy "Gap"

3.1.1 The "Gap" Between Compliance and Real World Fuel Economy

Real world tailpipe CO_2 emissions are higher, and real world fuel economy levels are lower, than the corresponding values from EPA standards compliance tests. This is because laboratory testing cannot reflect all of the factors that can affect real world operation, and, in particular, the city and highway tests used for compliance do not encompass the broad range of driver behavior and climatic conditions experienced by typical U.S. drivers.[A] In the rulemakings that established the National Program standards through MY2025, EPA and NHTSA applied a 20 percent fleet-wide fuel economy "gap," i.e., that average, fleet-wide real world fuel economy would be 20 percent lower than EPA compliance test values.[B] This 20 percent value was based on data from MY2004-2006.[1] For example, a vehicle with a fuel economy compliance test value of 30 mpg would be projected to have a real world fuel economy of 30 multiplied by 0.8 (equivalent to a 20 percent reduction) or 24 mpg. The inverse of 0.8 is 1.25, and a vehicle with a CO_2 emissions compliance test value of 300 grams/mile would be projected to have a real world CO_2 emissions value of 300 multiplied by 1.25 or 375 grams/mile.

As discussed in the Draft TAR, more recent data suggest that the gap between the 2-cycle compliance tests and the 5-cycle methodology values may have increased very slightly in the last decade. For example, the use of final MY2014 and final MY2015 data suggest that the fuel economy gap between 2-cycle data and 5-cycle data may now be approximately 21 percent.[2] EPA believes that further analysis is needed before incorporating such small changes into calculations of the overall gap. In addition, some analysis suggests that the gap between 2-cycle compliance tests and real world fuel economy may be increasing in recent years, but the evidence is not conclusive.[3] One factor which has clearly changed and can be quantified is ethanol content in gasoline. When the 20 percent fuel economy gap was first projected in 2005-2006, ethanol accounted for a small fraction of the gasoline pool. Consistent with our analysis in the Draft TAR, for the Proposed Determination, EPA adjusts for projected differences in the energy content due to increased ethanol penetration of retail gasoline relative to test fuel for MY2022 and beyond. Ethanol contains about 35 percent less energy than gasoline, on a volumetric basis, and EPA projects that average in-use gasoline will contain about 3.5 percent less energy in 2025 than it did in the 2005-2006 timeframe. Using the "base" 20 percent fuel economy gap between 2-cycle and 5-cycle data and the projected impact of the ethanol increase in 2025 yields an effective gap of 23 percent (or a fuel economy factor of 0.77), and this is the

[A] EPA has recognized that the "2-cycle" city and highway tests are not representative of real world fuel economy performance for over 30 years. From MY1985 through MY2007, EPA based new vehicle window labels on the fuel economy compliance test values adjusted downward by 10% for the city test and by 22% for the highway test. Beginning in MY2008, EPA has based vehicle labels on a 5-cycle methodology that includes three additional tests (reflecting high speed/high acceleration, hot temperature/air conditioning, and cold temperature operation) as well as a 9.5% downward fuel economy adjustment for other factors not reflected in the 5-cycle protocol.

[B] Note that this is an average fleet-wide value, in reality the true fuel economy gap is data driven and will be lower for some vehicles and higher for other vehicles. In general, all things being equal, today's data suggests that the gap is generally smaller for lower-fuel economy vehicles and greater for higher-fuel economy vehicles.

overall fuel economy gap that we use in this Proposed Determination analysis, which is consistent with that used in the Draft TAR. Multiplying 2-cycle fuel economy by 0.77 yields projected real world fuel economy.[C]

The fuel economy gap is data driven, so any 2025 projection involves uncertainty. EPA expects that, all other things being equal, as average fuel economy increases over time, the gap would likely increase as well. On the other hand, it is also possible that powertrain designs will be designed to be more robust in the future, which would impact the gap in the opposite direction.

3.1.2 Real World Fuel Economy and CO_2 Projections

Except when noted, CO_2 emissions and fuel economy values cited in this analysis represent standards compliance values. As discussed above, real world tailpipe CO_2 emissions are higher, and real world fuel economy levels are lower, than the corresponding values from the EPA standards compliance tests.

This has led to widespread public confusion as there are two sets of fuel economy “books,” one for fuel economy standards compliance (mandated by statute for cars) and one for the vehicle label estimates that EPA provides to consumers to estimate real world fuel economy. The projected real world fuel economy values shown below are the most meaningful fuel economy values for citizens and reporters as they provide a good comparison with label values, EPA Fuel Economy Trends report values, vehicle dashboard display values, and fuel economy calculations performed by some drivers, and also correspond to real world fuel consumption and CO_2 emissions.

Table 3.1 through Table 3.3 show EPA’s best projections of the real world CO_2 emissions and fuel economy values associated with the projected CO_2 standards compliance emissions levels presented throughout this report, as well as how "the numbers add up," for cars, trucks, and the combined car/truck fleet, respectively. These values use as a starting point the projected industry-wide CO_2 2-cycle targets. The first step is to “back out” the impact of the direct air conditioner refrigerant credits, since reducing leakage and/or substituting lower-GHG refrigerants will not increase real world fuel economy. Backing out these credits requires adding the value of the air conditioner refrigerant credits to the target values, as doing so increases the CO_2 value and decreases the projected real world fuel economy level. The sum of the 2-cycle target and the “backed out” air conditioner refrigerant credits is the “fuel economy-relevant adjusted 2-cycle CO_2 emissions value,” shown as the effective CO_2 value in the tables which can also be expressed as an effective mpg by dividing it into 8887 (which represents the number of grams of CO_2 that results from the combustion of a gallon of test gasoline). The second step is to multiply the adjusted 2-cycle, or effective mpg value by 0.77, the fuel economy “gap” factor discussed above. This step converts from the adjusted 2-cycle mpg to a real world, on-road mpg value. On-road tailpipe CO_2 emissions are projected by dividing the real world mpg value into 8488 (which represents the number of grams of CO_2 that results from the combustion of a gallon

[C] The corresponding CO2 "gap" is 1.24, i.e., multiplying 2-cycle tailpipe CO2 by 1.24 yields projected real world CO2 emissions. This 1.24 factor is actually less than the 1.25 factor used in the past because of the lower carbon content of ethanol.

of retail gasoline). Subtracting back the A/C leakage credit value provides an on-road CO_2 equivalent (CO_2 e) value as shown.

Table 3.1 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for Cars

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	171	51.9	13.8	5.0	0.8	191	46.6	5.8	185	48.1	.773	37.1	229	215
2022	165	53.9	13.8	5.0	1.0	185	48.1	6.0	179	49.8	.773	38.4	221	207
2023	159	56.0	13.8	5.0	1.2	179	49.7	6.2	172	51.5	.773	39.8	213	200
2024	153	58.1	13.8	5.0	1.5	173	51.3	6.5	167	53.3	.773	41.2	206	192
2025	147	60.3	13.8	5.0	1.7	168	53.0	6.7	161	55.2	.773	42.6	199	186

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2 e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2 e emissions performance.

Table 3.2 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for Trucks

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	238	37.4	17.2	7.2	1.9	264	33.7	9.1	255	34.9	.773	26.9	315	298
2022	228	39.0	17.2	7.2	2.4	255	34.9	9.6	245	36.2	.773	28.0	304	286
2023	219	40.6	17.2	7.2	2.8	246	36.1	10.0	236	37.7	.773	29.1	292	275
2024	210	42.3	17.2	7.2	3.3	238	37.4	10.5	227	39.1	.773	30.2	281	264
2025	202	44.0	17.2	7.2	3.8	230	38.6	11.0	219	40.6	.773	31.3	271	254

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2 e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2 e emissions performance.

Table 3.3 EPA Projections for Fleet-wide CO_2 Standards Compliance and On-road Performance for the Fleet

	2-Cycle							Adjustments to 2-Cycle to Reflect Real World Impacts			On-road			
MY	CO_2 Target (g/mi)	CO_2 Target As MPG	A/C Leakage Credit (g/mi)	A/C Efficiency Credit (g/mi)	Off-cycle Credit (g/mi)	Tailpipe CO_2 (g/mi)	MPG	A/C Efficiency & Off-cycle Credits (g/mi)	Effective CO_2 (g/mi)	Effective MPG	Gap	On-road MPG	On-road Tailpipe CO_2 (g/mi)	On-road CO_2e (g/mi)
2021	204	43.6	15.5	6.1	1.3	227	39.2	7.4	219	40.5	.773	31.3	272	256
2022	196	45.4	15.5	6.1	1.7	219	40.6	7.7	211	42.1	.773	32.5	261	246
2023	187	47.4	15.4	6.1	2.0	211	42.1	8.0	203	43.8	.773	33.8	251	236
2024	180	49.4	15.4	6.0	2.3	204	43.6	8.4	195	45.5	.773	35.1	242	226
2025	173	51.4	15.4	6.0	2.7	197	45.1	8.7	188	47.2	.773	36.4	233	218

Note: The on-road values reflect adjustments for both the historical 2-cycle-to-5-cycle gap as well as the projected ethanol content in retail gasoline, and corresponding energy content. The on-road CO_2 is calculated by dividing 8488, the estimated CO_2 grams/gallon from combustion of a gallon of retail gasoline, by the on-road MPG. The on-road CO_2 e column subtracts from the on-road tailpipe CO_2 values the A/C leakage value to yield a value that reflects overall real world CO_2 e emissions performance.

EPA projects the industry-wide real world fuel economy associated with the MY2025 GHG standards to be about 36 mpg. This value provides a good comparison with average label and Fuel Economy Trends values.

3.2 Fuel Prices and the Value of Fuel Savings

Fuel prices and the projection of fuel prices remain critical in the analysis of GHG and fuel economy standards. EPA has continued to use the methodology described in Chapter 10 of the Draft TAR, with some updates to the inputs used for this Proposed Determination. EPA continues to rely on the fuel price projections from the U.S. Energy Information Administration's (EIA) Annual Energy Outlook (AEO) for this analysis, updated to the AEO 2016 Reference Case (the Draft TAR analysis was based on AEO 2015). The Reference case projection is a business-as-usual trend estimate, given known technology and technological and demographic trends. EIA has published annual projections of energy prices and consumption levels for the U.S. economy since 1982 in its Annual Energy Outlook reports. These projections have been widely relied upon by federal agencies for use in regulatory analysis and for other purposes. Since 1994, EIA's annual forecasts have been based upon the agency's National Energy Modeling System (NEMS), which includes detailed representation of supply pathways, sources of demand, and their interaction to determine prices for different forms of energy. In addition to the AEO 2016 Reference Case as the central case, EPA has also included the AEO 2016 low and high fuel price cases as sensitivities. A comparison of these cases is presented below in Table 3.4.

Table 3.4 Gasoline Prices for Selected Years in Various AEO 2016 Cases (2015$)

	2025	2030	2040
AEO 2016 Reference Case	$ 2.97	$ 3.19	$ 3.81
AEO 2016 "Low" Case	$ 1.97	$ 2.04	$ 2.53
AEO 2016 "High" Case	$ 4.94	$ 5.17	$ 5.61

The retail fuel price forecasts presented in AEO 2016 span the period from 2015 through 2040. Measured in constant 2015 dollars, the AEO 2016 Reference Case projections of retail gasoline prices during calendar year 2025 is $2.97 per gallon, rising gradually to $3.81 by the year 2040 (these values include federal and state taxes). However, valuing fuel savings over the full lifetimes of passenger cars and light trucks affected by the standards for MYs 2022-25 requires fuel price forecasts that extend through nearly 2060, the last year during which a significant number of MY2025 vehicles will remain in service. Due to the difficulty in accurately projecting fuel prices over this long time span (as AEO projections span only through 2040), EPA has assumed constant fuel prices after the year 2040 for this Proposed Determination.

Figure 3.1 shows the three AEO 2016 fuel price cases used for this Proposed Determination, as compared to the AEO 2015 cases that had been used in the Draft TAR.

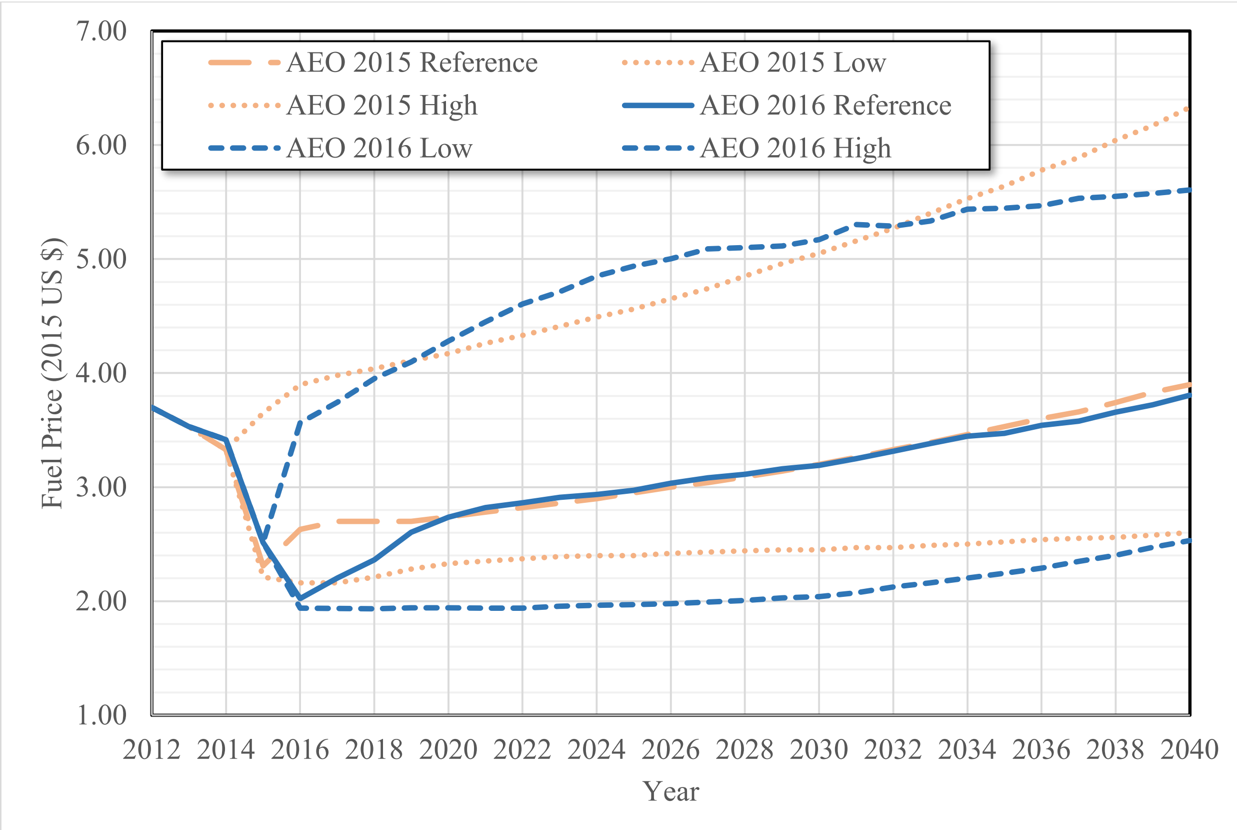


Figure 3.1 Comparing AEO 2016 Retail Fuel Price Projections to AEO2015 Projections

The value of fuel savings resulting from improved fuel economy and reduced GHG emissions to buyers of light-duty vehicles is determined by the retail price of fuel, which includes federal, state, and any local taxes imposed on fuel sales. Total taxes on gasoline, including federal, state, and local levies, averaged $0.41 per gallon during 2015. Because fuel taxes represent transfers of resources from fuel buyers to government agencies, rather than real resources that are consumed in the process of supplying or using fuel, their value must be deducted from retail fuel prices to determine the value of fuel savings resulting from more stringent GHG standards to the U.S. economy. When calculating the value of fuel saved by an individual driver, however, these taxes are included as part of the value of realized fuel savings. Over the entire period spanned by EPA's analysis, this difference causes each gallon of fuel saved to be valued by about $0.39 (in constant 2015 dollars) more from the perspective of an individual vehicle buyer than from the overall perspective of the U.S. economy.

3.3 Vehicle Mileage Accumulation and Survival Rates

EPA's analyses of benefits from GHG standards for passenger cars and light trucks, including GHG reductions, oil reductions, and fuel savings, begin by estimating the resulting changes in fuel use over the entire lifetimes of affected cars and light trucks. The change in total fuel consumption by vehicles produced during each of these model years is calculated as the difference in their total lifetime fuel use over the entire lifetimes of these vehicles as compared to a reference case.

EPA's approach for this analysis remains largely the same as that found in the Draft TAR, Chapter 10. Since the Draft TAR, EPA has updated a few key inputs related to vehicle lifetime survival rates and total vehicle miles traveled (VMT), as described in Table 3.5 and Table 3.6 below. These updates were made in order to align this analysis with inputs developed in conjunction with updates to the EPA MOVES 2014a model[4] since the official release of that model, which now has integrated new activity and population data sources from R.L. Polk, the U.S. Department of Transportation/Federal Highway Administration (FHWA), and the EIA Annual Energy Outlook 2016.[5] Continuing consistency with EIA, FHWA and MOVES remains a priority for these modeling inputs. Additionally, the MOVES model is also already used as part of other EPA rulemaking analyses, allowing this analysis to take advantage of updates from those efforts. These updates show a slight increase (approximately 1.8 percent) in overall vehicle VMT, especially in the early years of a vehicle's lifetime. Methodologies for the derivation of fuel savings and related benefits (including future year projections, VMT growth factor, and fuel cost per mile) from these inputs remain identical to those used in the Draft TAR (which are consistent with the 2012 FRM).

Table 3.5 Vehicle Survival Rates (from MOVES 2014[a])

VEHICLE AGE	ESTIMATED SURVIVAL FRACTION (CARS)	ESTIMATED SURVIVAL FRACTION (LIGHT TRUCKS)
0	1.000	1.000
1	0.997	0.991
2	0.994	0.982
3	0.991	0.973
4	0.984	0.960
5	0.974	0.941
6	0.961	0.919
7	0.942	0.891
8	0.920	0.859
9	0.893	0.823
10	0.862	0.784
11	0.826	0.741
12	0.788	0.697
13	0.718	0.651
14	0.613	0.605
15	0.510	0.553
16	0.415	0.502
17	0.332	0.453
18	0.261	0.407
19	0.203	0.364
20	0.157	0.324
21	0.120	0.288
22	0.092	0.255
23	0.070	0.225
24	0.053	0.198
25	0.040	0.174
26	0.030	0.153
27	0.023	0.133
28	0.013	0.117
29	0.010	0.102
30	0.007	0.089
31	0.002	0.027

Note: This table remains consistent with the values found in the Draft TAR.

Table 3.6 2015 Mileage Schedule (from MOVES 2014[a])

VEHICLE AGE	ESTIMATED VMT CARS	ESTIMATED VMT LIGHT TRUCKS
0	14,102	16,040
1	13,834	15,745
2	13,545	15,408
3	13,236	15,081
4	12,910	14,676
5	12,568	14,163
6	12,213	13,723
7	11,848	13,253
8	11,473	12,778
9	11,092	12,272
10	10,706	11,781
11	10,319	11,290
12	9,931	10,808
13	9,546	10,326
14	9,165	9,854
15	8,791	9,396
16	8,425	8,962
17	8,070	8,543
18	7,728	8,159
19	7,401	7,810
20	7,092	7,496
21	6,804	7,222
22	6,536	6,991
23	6,292	6,809
24	6,075	6,679
25	5,886	6,602
26	5,728	6,588
27	5,602	6,588
28	5,512	6,588
29	5,458	6,588
30	5,458	6,588
TOTAL	283,347	314,805

3.4 Fuel Economy Rebound Effect

3.4.1 Accounting for the Fuel Economy Rebound Effect

The rebound effect generally refers to the additional energy consumption that may arise from the introduction of a more efficient, lower cost energy service which offsets, to some degree, the energy savings benefits of that efficiency improvement.[6,7,8] In the context of light-duty vehicles

(LDVs), rebound effects might occur when an increase in vehicle fuel efficiency encourages people to drive more as a result of the lower cost per mile of driving. Because this additional driving consumes fuel and generates emissions, the magnitude of the rebound effect is one determinant of the actual fuel savings and emission reductions that will result from adopting stricter fuel economy or GHG emissions standards.

The rebound effect for personal vehicles can in theory be estimated directly from the change in vehicle use, in terms of vehicle miles traveled (VMT), which results from a change in vehicle fuel efficiency.[D] In practice, any attempt to quantify this "VMT rebound effect" (sometimes also labeled the "direct rebound effect," or "direct VMT rebound effect") is complicated by the difficulty in identifying an applicable data source from which the response to a significant improvement in fuel efficiency can be estimated. Analysts instead often estimate the VMT rebound indirectly as the change in vehicle use that results from a change in fuel cost per mile driven or a change in fuel price. When a fuel cost-per mile approach is used, it does not distinguish the relative contributions of changes in fuel efficiency and changes in fuel price to the rebound effect, since both factors are determinants of fuel cost-per mile.[E]

When expressed as positive percentages, the elasticities of vehicle use with respect to fuel efficiency or per-mile fuel costs (or fuel prices) give the percentage increase in vehicle use that results from a doubling of fuel efficiency (e.g., 100 percent increase), or a halving of fuel consumption or fuel price. For example, a 10 percent rebound effect means that a 20 percent reduction in fuel consumption or fuel price (and the corresponding reduction in fuel cost per mile) is expected to result in a two percent increase in vehicle use.

While we focus on the VMT rebound effect in our analysis of this program, there are at least two other types of rebound effects discussed in the transportation policy and economics literature. In addition to the direct VMT rebound effect, there is the "indirect" rebound effect, which typically refers to the purchase of other goods or services that consume energy with the costs savings from energy efficiency improvements. The last type of rebound effect is labeled the "economy-wide" rebound effect. This effect refers to the increased demand for energy throughout the whole economy in response to the reduced market price of energy that happens as a result of energy efficiency improvements.

Research on indirect and economy-wide rebound effects is scant. Given the limited literature and potential methodological shortcoming of the studies on LDV indirect and economy-wide rebound effects, the rebound effect discussed in this section refers solely to the effect of increased fuel efficiency on vehicle use. The terms "VMT rebound effect," "direct VMT rebound effect," and "rebound effect" can be used interchangeably, and they need to be distinguished from other rebound effects that could potentially impact the fuel savings and emissions reductions from EPA's LDV standards such as the "indirect rebound effect." To restate, the rebound effect discussed in this section refers solely to the effect of increased fuel efficiency on vehicle use.

[D] Vehicle fuel efficiency is more often measured in terms of fuel consumption (gallons per mile) rather than fuel economy (miles per gallon) in rebound estimates.

[E] Fuel cost-per mile is equal to the price of fuel in dollars per gallon divided by fuel economy in miles per gallon (or multiplied by fuel consumption in gallons per mile), so this figure declines when a vehicle's fuel efficiency increases.

3.4.2 Summary of Historical Literature on the LDV Rebound Effect

This section provides a brief summary of historical literature on the LDV rebound effect. It is important to note that a majority of the studies previously conducted on the rebound effect rely on data from the 1950–1990s. While these older studies provide valuable information on the potential magnitude of the rebound effect, studies that include more recent information (e.g., data within the last decade) may provide more reliable estimates of how the MY2022-2025 standards will affect future driving behavior. Recent studies on LDV rebound effects that have become available since the 2012 LDV final rule and also reviewed for the Draft TAR are summarized in Section 3.4.3 below. The one additional study on the direct rebound effect, added to this review since the Draft TAR, is by Wang and Chen (2014).

Estimates based on aggregate U.S. vehicle travel data published by the U.S. Department of Transportation, Federal Highway Administration, covering the period from roughly 1950 to 1990, have found long-run rebound effects on the order of 10–30 percent. Some of these studies are summarized in the following two tables, Tables 3.7 and 3.8. The agency added in more recent studies by Small and Van Dender (2007a) and Hymel, Small and Van Dender (2010) into Table 3.8. In addition, Table 3.9 below provides estimates of the rebound effect using U.S. household survey data. The agency added in more recent studies by Bento (2009) and Wadud et al. (2009) into Table 3.9.

Table 3.7 Estimates of the Rebound Effect Using U.S. Aggregate Time-Series Data on Vehicle Travel

Author (year)	Short-Run	Long-Run	Time Period
Mayo & Mathis (1988)	22%	26%	1958-84
Gately (1992)	9%	9%	1966-88
Greene (1992)	Linear 5-19% Log-linear 13%	Linear 5-19% Log-linear 13%	1957-89
Jones (1992)	13%	30%	1957-89
Schimek (1996)	*5-7%*	*21-29%*	1950-94

Source: Sorrell and Dimitropolous (2007) table 4.6.[9]

Table 3.8 Estimates of the Rebound Effect Using U.S. State-Level Data

Author (year)	Short-Run	Long-Run	Time Period
Haughton & Sarkar (1996)	9-16%	22%	1973-1992
Small and Van Dender (2005 and 2007a)	4.5% 2.2%	22.2% 10.7%	1966-2001 1997-2001
Hymel, Small and Van Dender (2010)	*4.7%* *4.8%*	*24.1%* *15.9%*	1966-2004 1984-2004

Source: Sorrell and Dimitropolous (2007) table 4.7 and Small and Van Dender (2007a) and (2010)

Table 3.9 Estimates of the Rebound Effect Using U.S. Household Survey Data

Author (year)	Estimate of Rebound Effect	Time Period
Goldberg (1996)	0%	CES 1984-90
Greene, Kahn, and Gibson (1999a)	23%	EIA RTECS 1979-1994
Pickrell & Schimek (1999)	4-34%	NPTS 1995 Single year
Puller & Greening (1999)	49%	CES 1980-90 Single year, cross-sectional
West (2004)	87%	CES 1997 Single year
Bento (2009)	34%	NHTS 2001
Wadud et al. (2009)	*1-25%*	CES 1984-2003

Source: Sorrell and Dimitropolous (2007) and Bento (2009) and Wadud et al. (2009)

While studies using national (Table 3.7) and state level (Table 3.8) data have found a relatively consistent range of long-run estimates of the rebound effect, household surveys display more variability (Table 3.9). One explanation for the variability in the household survey estimates is that these studies consistently find that the magnitude of the rebound effect differs according to the number of vehicles a household owns, and the average number of vehicles owned per household differs among the surveys used to derive these estimates. Still another possibility is that it is difficult to distinguish the impact of fuel cost-per mile on vehicle use from that of other, unobserved factors. For example, commuting distance might influence both the choice of the vehicle as well as VMT. Residential density may also influence both fuel cost-per mile and VMT, since households in urban areas are likely to simultaneously face both higher fuel prices and shorter travel distances. Also, given that household data tends to be collected on an annual basis, there may not be enough variability in the fuel price data to estimate the magnitude of the rebound effect.[10]

It is important to note that some of these studies actually quantify the price elasticity of gasoline demand (e.g., Puller & Greening (1999)[11]) or the elasticity of VMT with respect to the price of gasoline (e.g., Pickrell & Schimek (1999)[12]), rather than the elasticity of VMT with respect to fuel efficiency or the fuel cost per mile of driving. These latter measures more closely match the definition of the fuel economy rebound effect. In fact, most studies cited above do not estimate the direct measure of the fuel economy rebound effect (i.e., the increase in VMT attributable to an increase in fuel efficiency).

Another important distinction among studies of the rebound effect is whether they assume that the effect is constant, or varies over time in response to the absolute levels of fuel costs, personal income, or household vehicle ownership. Most studies using aggregate annual data for the U.S. assume a constant rebound effect, although some of these studies test whether the effect can vary as changes in retail fuel prices or average fuel efficiency alter fuel cost per mile driven. Many studies using household survey data estimate significantly different rebound effects for households owning varying numbers of vehicles, with most finding that the rebound effect is larger among households that own more vehicles.[F]

Some of the more recent studies (Small and Van Dender (2007), Hymel, Small, and Van Dender ((2010), (2012)), using both state-level and national data, conclude that the rebound effect varies directly in response to changes in personal income, as well as fuel costs. These more recent studies published between 2007 and 2012 indicate that the rebound effect has decreased over time as incomes have risen and, until recently, fuel costs as a share of total monetary travel costs have generally decreased.[G] One theoretical argument for why the rebound effect should vary over time is that the responsiveness to the fuel cost of driving will be larger when it is a larger proportion of the total cost of driving. For example, as incomes rise, the responsiveness to the fuel cost per mile of driving will decrease if people view the time cost of driving – which is likely to be related to their income levels – as a larger component of the total cost.

Small and Van Dender (2007)[13] combined time series data for each of the 50 states and the District of Columbia to estimate the rebound effect, allowing the magnitude of the rebound to vary over time. For the time period from 1966–2001, their study found a long-run rebound effect of 22.2 percent, which is consistent with previously published studies. But for the five year period (1997–2001) estimated in their study, the long-run rebound effect decreased to 10.7 percent. Furthermore, when the authors updated their estimates with data through 2004, the long-run rebound effect for the most recent five year period (2000–2004) dropped to six percent.[14]

Hymel, Small and Van Dender (2010)[15] extended the Small and Van Dender model by adding congestion as an endogenous variable. Although controlling for congestion increased their estimates of the rebound effect, Hymel, Small and Van Dender also found that the rebound effect was declining over time. For the time period from 1966–2004, they estimated a long-run rebound effect of 24 percent, while for 2004 they estimated a long-run rebound effect of 13 percent.

Research conducted by David Greene (2012)[16] under contract with EPA further appears to support the theory that the magnitude of the rebound effect "is by now on the order of 10

[F] Five of the household survey studies evaluated in Table 3.9 found that the rebound effect varies in relation to the number of household vehicles. Of those five studies, three found that the rebound effect rises with higher vehicle ownership, and two found that it declines. The three studies with rebound estimates that increase with higher household vehicle ownership are: Greene, D., and Hu, P., "The Influence of the Price of Gasoline on Vehicle Use in Multi-vehicle Households," Transportation Research Record (1984), pp. 19-24; Hensher, D., Milthorpe, F. and Smith, N., "The Demand for Vehicle Use in the Urban Household Sector: Theory and Empirical Evidence," Journal of Transport Economics and Policy, 24:2 (1990), pp. 119-137; and Walls, M., Krupnick A., and Hood, H., "Estimating the Demand for Vehicle-Miles Traveled Using Household Survey Data: Results from the 1990 Nationwide Personal Transportation Survey," Discussion Paper ENR 93-25, Energy and Natural Resources Division, Resources for the Future, Washington, D.C., 1993.

[G] While real gasoline prices have varied over time, fuel costs (which reflect both fuel prices and fuel efficiency) as a share of total vehicle operating costs declined substantially from the mid-1970s until the mid-2000s when the share increased modestly (see Greene (2012)). With the recent decline in world petroleum prices, total vehicle operating costs have declined recently as well.

percent."[H] Like Small and Van Dender, Greene finds that the VMT rebound effect could decline modestly over time as household income rises and travel costs increase. Over the entire time period analyzed (1966–2007), Greene found that fuel prices had a statistically significant impact on VMT, while fuel efficiency did not, which is similar to Small and Van Dender's prior finding. From this perspective, if the impact of fuel efficiency on VMT is not statistically significant, the VMT rebound effect could be zero. When Small and Van Dender tested whether the elasticity of vehicle travel with respect to the price of fuel was equal to the elasticity with respect to the rate of fuel consumption (gallons-per mile), they found that the data could not reject this hypothesis. Therefore, Small and Van Dender estimated the rebound effect as the elasticity of travel with respect to fuel cost-per mile.

In contrast, Greene's research rejected the hypothesis of equal elasticities for gasoline prices and fuel efficiency. In spite of this result, Greene also tested Small and Van Dender's formulation which allows the elasticity of fuel cost-per mile to decrease with increasing per capita income. The results of estimation using national time series data confirmed the results obtained by Small and Van Dender using a time series of state level data. When using Greene's preferred functional form, the projected rebound effect is approximately 12 percent in 2008, and drops to 10 percent in 2020 and to nine percent in 2030.

Of the studies listed in Table 3.9, the studies that are most recent are by Bento et al.[17] and Wadud et al.[18] Bento et al. combined demographic characteristics of more than 20,000 U.S. households, the manufacturer and model of each vehicle they owned, and their annual usage of each vehicle from the 2001 National Household Travel Survey with detailed data on fuel economy and other attributes for each vehicle model obtained from commercial publications. The authors aggregated vehicle models into 350 categories representing combinations of manufacturer, vehicle type, and age, and use the resulting data to estimate the parameters of a complex model of households' joint choices of the number and types of vehicles to own, and their annual use of each vehicle.

Bento et al. estimate the effect of vehicles' operating cost-per mile, including fuel costs – which depend in part on each vehicle's fuel economy – as well as maintenance and insurance expenses, on households' annual use of each vehicle they own. Combining the authors' estimates of the elasticity of vehicle use with respect to per mile operating costs with the reported fraction of total operating costs accounted for by fuel (slightly less than one-half) yields estimates of the rebound effect. The resulting values vary by household composition, vehicle size and type, and vehicle age, ranging from 21 to 38 percent, with a composite estimate of 34 percent for all households, vehicle models, and ages. The smallest values apply to new luxury cars, while the largest estimates are for light trucks and households with children, but the implied rebound effects differ little by vehicle age.

Wadud et al. combine data on U.S. households' demographic characteristics and expenditures on gasoline over the period 1984–2003 from the Consumer Expenditure Survey with data on gasoline prices and an estimate of the average fuel economy of vehicles owned by individual households (constructed from a variety of sources). They employ these data to explore variation in the sensitivity of individual households' gasoline consumption to differences in income,

[H] p. 15, Greene, D., Rebound 2007: Analysis of U.S. light-duty vehicle travel statistics. Energy Policy (2010), doi:10.1016/j.enpol.2010.03.083.

gasoline prices, the number of vehicles owned by each household, and their average fuel economy. Using an estimation procedure intended to account for correlation among unmeasured characteristics of households and among estimation errors for successive years, the authors explore variation in the response of fuel consumption to fuel economy and other variables among households in different income categories, and between those residing in urban and rural areas.

Dividing U.S. households into five equally-sized income categories, Wadud et al. estimate rebound effects ranging from 1–25 percent, with the smallest estimates (8 percent and 1 percent) for the two lowest income categories, and significantly larger estimates for the middle (18 percent) and two highest income groups (18 and 25 percent). In a separate analysis, the authors estimate rebound effects of seven percent for households of all income levels residing in U.S. urban areas, and 21 percent for rural households.

Since there has been little variation in fuel economy in the data over time, isolating the impact of fuel economy on VMT can be difficult using econometric analysis of historical data. Therefore, studies that estimate the rebound effect using time series data often examine the impact of gasoline prices on VMT, or the combined impact of both gasoline prices and fuel economy on VMT, as discussed above. However, these studies may overstate the potential impact of the rebound effect resulting from this rule, if people are more responsive to changes in fuel price than the variable directly of interest, fuel economy.

There is some evidence in the literature that consumers are more responsive to an increase in prices than to a decrease in prices. At the aggregate level, Dargay and Gately (1997) and Sentenac-Chemin (2012)[19] have provide some evidence that demand for transportation fuel is asymmetric. In other words, given the same size change in prices, the response to a decrease in gasoline price is smaller than the response to an increase in gasoline price. Gately (1993)[20] has shown that the response to an increase in oil prices can be on the order of five times larger than the response to a price decrease. Furthermore, Dargay and Gately and Sentenac-Chemin also find evidence that consumers respond more to a large shock than a small, gradual change in fuel prices. Since these standards would decrease the cost of driving gradually over time, it is possible that the rebound effect would be much smaller than some of the historical estimates included in the literature. Greene also notes that the resultant data from such gradual changes could make discernment of such an effect difficult.

3.4.3 Review of Recent Literature on LDV Rebound since the 2012 Final Rule

Recent studies on LDV rebound effects that have become available since the 2012 LDV final rule and are consistent with those discussed in the Draft TAR are summarized in Section 3.4.3 below. The one additional study on the direct rebound effect reviewed since the Draft TAR is by Wang and Chen (2014). Only a limited amount of work has been conducted to examine the rebound effect of electric vehicles so most of the studies of light-duty vehicle rebound effects focus on a change in gasoline prices. Below is a brief summary of the results of these recent studies.

Using data on household characteristics and vehicle use from the 2009 Nationwide Household Transportation Survey (NHTS), Su (2012)[21] analyzes the effects of locational and demographic factors on household vehicle use, and investigates how the magnitude of the rebound effect varies with vehicles' annual use. Using variation in the fuel economy and per-mile cost of and detailed controls for the demographic, economic, and locational characteristics of the households that owned them (e.g., road and population density) and each vehicle's main driver (as identified by survey respondents), the author employs specialized regression methods to capture the variation in the rebound effect across ten different categories of vehicle use.

Su estimated that the overall rebound effect for all vehicles in the sample averaged 13 percent, and that its magnitude varied from 11–19 percent among the ten different categories of annual vehicle use. The smallest rebound effects were estimated for vehicles at the two extremes of the distribution of annual use – those driven comparatively little, and those used most intensively – while the largest estimated effects applied to vehicles that were driven slightly more than average. Controlling for the possibility that high-mileage drivers respond to the increased importance of fuel costs by choosing vehicles that offer higher fuel economy narrowed the range of Su's estimated rebound effects slightly (to 11–17 percent), but did not alter the finding that they are smallest for lightly- and heavily-driven vehicles and largest for those with slightly above average use.

Linn (2013)[22] also uses the 2009 NHTS to develop a linear regression approach to estimate the relationship between the VMT of vehicles belonging to each household and a variety of different factors: fuel costs, vehicle characteristics other than fuel economy (e.g., horsepower, the overall "quality" of the vehicle), and household characteristics (e.g., age, income). Linn reports a fuel economy rebound effect with respect to VMT of between 20–40 percent.

One interesting result of the study is that when the fuel efficiency of all vehicles increases, which would be the long-run effect of rising fuel efficiency standards, two factors have opposing effects on the VMT of a particular vehicle. First, VMT increases when that vehicle's fuel efficiency increases. But the increase in the fuel efficiency of the household's other vehicles causes the vehicle's own VMT to decrease. Since the effect of a vehicle's own fuel efficiency is larger than the other vehicles' fuel efficiency, VMT increases if the fuel efficiency of all vehicles increases proportionately. Linn also finds that VMT responds much more strongly to vehicle fuel economy than to gasoline prices, which is at variance with the Hymel et al. and Greene results discussed above.

Like Su and Linn, Liu et al. (2014)[23] also employed the 2009 NHTS to develop an elaborate model of an individual household's choices about how many vehicles to own, what types and ages of vehicles to purchase, and how much combined driving to do using all of them. Their analysis used a complex mathematical formulation and statistical methods to represent and measure the interdependence among households' choices of the number, types, and ages of vehicles to purchase, as well as how intensively to use them.

Liu et al. employed their model to simulate variation in households' total vehicle use to changes in their income levels, neighborhood characteristics, and the per-mile fuel cost of driving averaged over all vehicles each household owns. The complexity of the relationships among the number of vehicles owned, their specific types and ages, fuel economy levels, and use incorporated in their model required them to measure these effects by introducing variation in income, neighborhood attributes, and fuel costs, and observing the response of households' annual driving. Their results imply a rebound effect of approximately 40 percent in response to significant (25–50 percent) variation in fuel costs, with almost exactly symmetrical responses to increases and declines.

Frondel and Vance (2013)[24] use panel estimation methods and household diary travel data collected in Germany between 1997 and 2009 to identify an estimate of a private transport rebound value. The study focuses on single-car households that did not change their car ownership over the maximum three years each household was surveyed. Failing to reject the null hypothesis of a symmetric price response, they find a rebound effect for single-vehicle households of 46–70 percent (though we discuss further below the limitations in applying findings of studies from other countries to U.S. rebound).

Gillingham (2014)[25] analyzed variation in the use of more than five million new vehicles purchased in California during the years 2001–03 over the first several years of their lifetimes, focusing particularly on the response of buyers' use of new vehicles to geographic and temporal variation in fuel prices. His sample consists predominantly of personal vehicles (87 percent), but also includes some purchased by businesses, rental car companies, and government. He estimates the effect of differences in the average of monthly fuel prices on their monthly average vehicle use over the time – at a county level, since being purchase – focusing his analysis on vehicles that have been purchased new and have been in service for six to seven years. The author also explores how the effect of fuel prices on vehicle use varies with vehicle use, buyer type and household income.

Gillingham relies exclusively on the effect of variation in fuel prices and does not involve vehicles' fuel economy. He reports an overall average effect of fuel prices on vehicle use that corresponds to a rebound effect of 22 percent, rising to 23 percent when he controls for the potential effect of gasoline demand on its retail price. He finds little evidence of variation in the rebound effect among buyer types. Based on the nature of his data and estimation procedure, he interprets his estimates as implying that vehicle use responds fully to changes in fuel prices after approximately two years.

Gillingham's results suggest that the vehicle-level responsiveness to fuel price increases with income. Gillingham hypothesizes that the increase in the per-vehicle rebound effect with higher incomes may relate to wealthier households having more discretionary driving or switching between flying and driving. Alternatively, wealthier households tend to own more vehicles and it is possible that within-household switching of vehicles to other more efficient vehicles in the household may account for the greater responsiveness at higher income levels.

In contrast to Gillingham's results, Wang and Chen (2014)[26] examine the variation of fuel price elasticity of VMT across income groups using a system of structural equations with VMT and fuel efficiency (i.e., miles per gallon) as endogenous variables from the 2009 National Household Travel Survey. They find that the rebound effect is only significant for the lowest income households (up to $25,000). Wang and Chen hypothesize that travel demand for these households are far from saturation, therefore getting more fuel efficient cars provides the opportunity to fulfil so called "latent demand."

Hymel and Small (2015)[27] revisit the simultaneous equations methodology of Small and Van Dender (2007) and Hymel, Small and Van Dender (2010) to see whether their previous estimates of the VMT rebound effect have changed by adding in more recent data from the late 2000 time period (e.g., 2005–2009). Consistent with previous results, the VMT rebound effect declines with increasing income and urbanization, and it increases with increasing fuel cost. By far the most important of these sources of variation is income, whose effect is large enough to greatly reduce the projected rebound effect for time periods of interest to current policy decisions. The best estimate of the long-run light-duty vehicle rebound effect over the years 2000–2009 is 17.8 percent, when evaluated at average values of income, fuel cost, and urbanization in the U.S. during that time period.

The recent study by Hymel and Small also finds a strengthening of the VMT rebound effect for the years 2003–2009 compared to the results for time periods from their previous research, suggesting that some additional unaccounted for factors have increased the rebound effect. Three potential factors are hypothesized to have caused the upward shift in the VMT rebound effect in the 2003–2009 time period: (1) media coverage, (2) price volatility, and (3) asymmetric response to price changes.[I] It should be noted that the while media coverage and volatility are important to understand the rebound effect based upon fuel prices, they may not be as relevant to the rebound effect due to fuel efficiency. These results show strong evidence of asymmetry in responsiveness to price increases and decreases. Results suggest that a rebound adjustment to fuel price rises takes place quickly; the rebound response elasticity is large in the year of, and the first year following, a price rise, then diminishes to a smaller value. The rebound response to price decreases occurs more slowly.

Hymel and Small find that there is an upward shift in the rebound effect of roughly 2.5 to 2.8 percentage points starting in 2003. Results suggest that the media coverage and volatility variables may explain about half of the upward shift in the LDV rebound effect in the 2003–2009 time period. Nevertheless, these influences are small enough in magnitude that they do not fully offset the downward trend in VMT response elasticities due to higher incomes and other factors. Hence, even assuming that the variables retain their 2003–2009 values into the indefinite future, they would not prevent a further diminishing of the magnitude of the rebound effect if incomes continue to grow at anything like historic rates.

West et al. (2015)[28] attempt to estimate the VMT rebound effect using household level data from Texas using a discontinuity in the eligibility requirements for the 2009 U.S. "Cash for Clunkers" program, which incentivized eligible households to purchase more fuel-efficient vehicles. Households that owned "clunkers" with a fuel economy of 18 miles per gallon (MPG) or less were eligible for the subsidy, while households owning clunkers with an MPG of 19 or more were ineligible. The empirical strategy of the paper is to compare the fuel economy of vehicle purchases and subsequent vehicle miles traveled of "barely eligible" households to those households who were "barely ineligible."

The paper finds a meaningful discontinuity in the fuel economy of new vehicles purchased by Cash for Clunker-eligible households relative to ineligible households. Those authors report that the increases in fuel economy realized by households who scrapped low fuel economy vehicles in response to the substantial financial incentives offered under the federal "Cash for Clunkers" program were not accompanied by increased use of the higher-MPG replacement vehicles they purchased because of the vehicle's other attributes. Households chose to buy cheaper, smaller and lower-performing vehicles. As a result, they did not drive any additional miles after the

[I] The media coverage variable is measured by constructing measures of media coverage based upon gas-price related articles appearing in the New York Times newspaper. Using the ProQuest historical database, they tally the annual number of article titles containing the words gasoline (or gas) and price (or cost). They then form a variable equal to the annual fraction of all New York Times articles that are gas-price-related. This fraction ranged from roughly 1/4000 during the 1960s to a high of 1/500 in 1974.

purchase of the fuel efficient vehicle. They conclude there is no evidence of a rebound effect in response to improved fuel economy from the Cash for Clunkers program.

It may be difficult to generalize the VMT response from the Cash for Clunkers program to a program for LDV GHG/fuel economy standards. Throughout this and all previous analyses of the likely effects of federal regulations to require increased fuel economy and reduce vehicles' GHG emissions, EPA and NHTSA have stressed that manufacturers can achieve the required improvements without compromising the performance, passenger-, cargo-carrying, and towing capacity, safety, or other attributes affecting the utility buyers and owners derive from the vehicles they choose to purchase. The Cash for Clunkers program was a one-time program for a fixed fleet of existing vehicles with specific characteristics. Their study may not provide useful implications about the likely response of vehicle use to required increases in fuel economy that are achieved through temporary incentive programs offered during recessions.

More recently, De Borger et al. (2016)[29] analyze the response of vehicle use to changes in fuel economy among a sample of nearly 350,000 Danish households owning a single vehicle, of which almost one-third replaced it with a different model sometime during the period from 2001 to 2011. By comparing the change in households' driving from the early years of this period to its later years among those who replaced their vehicles during the intervening period to that among households who kept their original vehicles, the authors claim to isolate the effect of changes in fuel economy on vehicle use from those of other factors. Their data allow them to control for the effects of important household characteristics and vehicle features other than fuel economy on vehicle use. They use complex statistical methods to account for the fact that some households replacing their vehicles may have done so in anticipation of changes in their driving demands (rather than the reverse), as well as for the possibility that some households who replaced their cars may have done so because their driving behavior was more sensitive to fuel prices than other households.

De Borger et al. measure the rebound effect from the change in households' vehicle use in response to changes in fuel economy that are a consequence of their decisions to replace the vehicles they owned previously. Thus they are able to directly estimate the fuel economy rebound effect itself, in contrast to other research that relies on indirect measures. Their preferred estimates span a very narrow range – from 8–10 percent – and vary only minimally in response to different statistical estimation procedures. They also vary little depending on whether the data sample is restricted to households that replaced their vehicles, in which case the rebound effect is identified exclusively by their responses to changes in fuel economy of varying magnitudes, or also includes households that did not replace their vehicles, and is thus identified partly by differences between their responses to varying fuel economy and changes in driving among households with vehicles whose fuel economy remained unchanged. Finally, De Borger et al. find no evidence that the rebound effect is smaller among lower-income households than among their higher-income counterparts. We discuss further below the limitations in applying findings of studies from other countries to U.S. rebound.

Gillingham et al. (2016)[30] undertake a summary and review of the general rebound literature including, for example, rebound effects from LDVs as well as electricity used in stationary applications. The literature suggests that differences in estimates of the rebound effect stem from its varying definitions, as well as variation in the quality of data and empirical methodologies used to estimate it. Gillingham et al. seek to clarify the definition of each of the channels of the rebound effect and critically assess the state of the literature that estimates its magnitude.

Gillingham et al. note that most analyses assume a “zero cost breakthrough” (ZCB) – their term for an improvement in efficiency that results in energy savings and related energy or fuel cost savings, but does not have associated increased costs of technology or implementation. Thus, the authors argue, most analyses do not reflect the true costs of a “policy-induced improvement”, noting: "In most cases when there is an energy efficiency policy there are also changes in costs and attributes, the responses to which are difficult to disentangle empirically. To analyze such an energy efficiency policy, it is essential to know all of the pertinent consumer and market responses to the improved efficiency, changed attributes, and increased cost...most studies that aim to estimate the rebound effect have an exogenous increase in energy efficiency in mind; fewer are examining an actual energy efficiency policy." Failing to account for the increased costs of equipment and/or implementation of a policy-induced improvement, Gillingham et al. caution may result in different estimates of the rebound effect compared to a ZCB improvement in efficiency.

Gillingham et al. also provide a list of what they consider to be relevant rebound elasticities that can provide guidance to policymakers, with a focus on studies of overall demand or household-level demand. According to the authors, the studies are selected both because they are more recent and use rigorous empirical methods such as panel data methods, experimental designs, and quasi-experimental approaches.

Of the selected studies, four focus on VMT elasticities for light-duty vehicles in developed countries. For the Frondel and Vance study (cited above), which reported a short-run elasticity of VMT demand for Germany for the time period from 1997–2009, Gillingham et al. chose the 46 percent value.[J] Barla (2009)[31] found a short-run elasticity of VMT for Canada from 1990–2004 of eight percent. Gillingham (2014) (cited above) found a California medium-run new vehicle elasticity of VMT demand for the time period 2001–2009 of 23 percent. Small and Van Dender (2007) (cited previously) found a U.S. short-run elasticity of VMT demand for the time period from 1966–2001 of roughly five percent.

It is not clear whether studies of LDV VMT rebound estimates for countries different from the U.S. would provide estimates that are appropriate to the U.S. context. For example, European countries have higher fuel prices and more transit options, both factors which would possibly produce a VMT rebound effect that is higher than in the U.S.

3.4.4 Basis for Rebound Effect Used in this Proposed Determination

As the preceding discussion indicates, there is a wide range of estimates for both the historical magnitude of the rebound effect and its projected future value, and there is some evidence that the magnitude of the rebound effect appears to be declining over time for those studies that look at VMT time trends. The recent literature is mixed, with some studies supporting relatively modest direct VMT rebound estimates and other studies suggesting a higher rebound effect. Some of these studies come to these varied conclusions despite using the same data set.

[J] Gillingham et al. believe that this value is derived by more successfully holding exogenous factors constant in the Frondel and Vance study.

EPA uses a single point estimate for the direct VMT rebound effect as an input to the agency's analyses. Based on a combination of historical estimates of the rebound effect and more recent analyses, an estimate of 10 percent for the long-run rebound effect is used for evaluating the MY2022–2025 standards for this Proposed Determination (i.e., we assume a 10 percent decrease in fuel cost per mile from the standards would result in a 1 percent increase in VMT). This rebound effect does not include "indirect" or "economy-wide" rebound effects.

As mentioned above, for the reasons described in Section 3.4.2, historical estimates of the rebound effect may overstate the effect of a gradual decrease in the cost of driving due to the standards. As a consequence, a value on the low end of the historical estimates is likely to provide a more reliable estimate of its magnitude during the period spanned by the analysis of the impacts of the MYs 2022–2025 standards. Studies that produce an aggregate measure of the rebound effect are most applicable to estimating the overall VMT effects of the LDV standards. The 10 percent estimate lies at the bottom of the 10–30 percent range of estimates for the historical, aggregate rebound effect in most research, and at the upper end of the 5–10 percent range of estimates for the future rebound effect reported in the relatively recent studies by Small, Hymel and Van Dender and Greene.

Both Small, Hymel and Van Dender and Greene find that the rebound effect decreases as household incomes rise. As incomes rise, the value of time spent driving becomes a larger fraction of total travel costs so that vehicle use becomes less responsive to variations in fuel costs. Since the AEO 2016 projects that household incomes will be rising throughout the analysis period for these standards, EPA believes that it is appropriate to factor in studies that account for income on the rebound effect. Wadud et al. (2009) and Gillingham (2014) find that household and individual-vehicle rebound increases, respectively, with increases in household income. On the other hand, Wang and Chen (2014) find that only low income households have a rebound effect while De Borger et al. (2016) find no evidence that the rebound effect differs between low households in Denmark and their higher income counterparts. Thus, the evidence of how the rebound effect varies between households across different income classes is mixed and inconclusive.

We believe that the rebound values that are most applicable to quantifying the impact of these standards on VMT are based on overall aggregate rebound effects as the fuel efficiency of the U.S.'s LDV fleet increases over time. This suggest that the Small, Hymel and Van Dender and Greene estimates are most relevant for this analysis. Su, Linn and Liu et al., each using NHTS 2009 data, find rebound effects that vary from 11–40 percent based upon household survey data. These widely different results based upon survey data from the same year suggest that these studies may not necessarily provide reliable estimates of the VMT rebound effect.

Gillingham et al. (2016) cite four studies that focus on VMT elasticities for light-duty vehicles in developed countries. Two of the four studies (for the U.S. and Canada) have short-run VMT elasticity values below the 10 percent figure. The study for California has per-vehicle rebound value of 23 percent, and does not reflect the reduced use of other vehicles in multi-vehicle household fleets. A study for Germany has a considerably higher value, roughly 46 percent. A recent study by De Borger at al. found a rebound value in the range of 10 percent for Denmark. As noted previously, it is not clear whether studies of VMT LDV rebound estimates for countries different from the U.S. would provide estimates that are appropriate to the U.S. context.

In summary, the 10 percent value was not derived from a single point estimate from a particular study, but instead represents a reasonable compromise between historical estimates of the rebound effect and forecasts of its projected future value, based on an updated review of the literature on this topic.

3.5 Energy Security Impacts

The National Program is designed to require improvements in the fuel economy of light-duty vehicles and, thereby, reduce fuel consumption and GHG emissions. In turn, the program helps to reduce U.S. petroleum imports. A reduction of U.S. petroleum consumption and imports reduces both financial and strategic risks caused by potential sudden disruptions in global oil supply, thus increasing U.S. energy security. This section summarizes EPA's estimates of U.S. oil import reductions and energy security benefits of the GHG vehicle standards for model years 2022–2025.

3.5.1 Implications of Reduced Petroleum Use on U.S. Imports

U.S. energy security is generally considered as the continued availability of energy sources at an acceptable, stable price. Most discussion of U.S. energy security revolves around the topic of the economic costs of U.S. dependence on oil imports. While the U.S. has reduced its consumption and increased its production of oil in recent years, it still relies on oil from potentially unstable sources outside of the U.S. and the U.S. oil price will remain tightly linked to the global oil market. In addition, oil exporters with a large share of global production have the ability to raise the price of oil by exerting the monopoly power associated with a cartel, the Organization of Petroleum Exporting Countries (OPEC), to restrict oil supply relative to demand. These factors contribute to the vulnerability of the U.S. economy to episodic oil shocks to either the global supply of oil or world oil price spikes.

In 2015, U.S. expenditures for imports of crude oil and petroleum products, net of revenues for exports, were $85 billion and expenditures on both imported oil and domestic petroleum and refined products totaled $350 billion (2015$).[32] Recently, as a result of strong growth in domestic oil production mainly from tight shale formations, U.S. production of oil has increased while U.S. oil imports have decreased. For example, from 2012 to 2015, domestic oil production increased by 35 percent while oil imports decreased by 38 percent.[33] While oil import costs have declined since 2011, and declined sharply as the world oil price fell from roughly $100/barrel in 2014 to $52/barrel in 2015, total oil expenditures (domestic and imported) remained near historical highs through 2014. Post-2016 oil expenditures are projected (AEO 2016) to remain between double and triple the average inflation-adjusted levels experienced by the U.S. from 1986 to 2002 (see Figure 3.2 below).

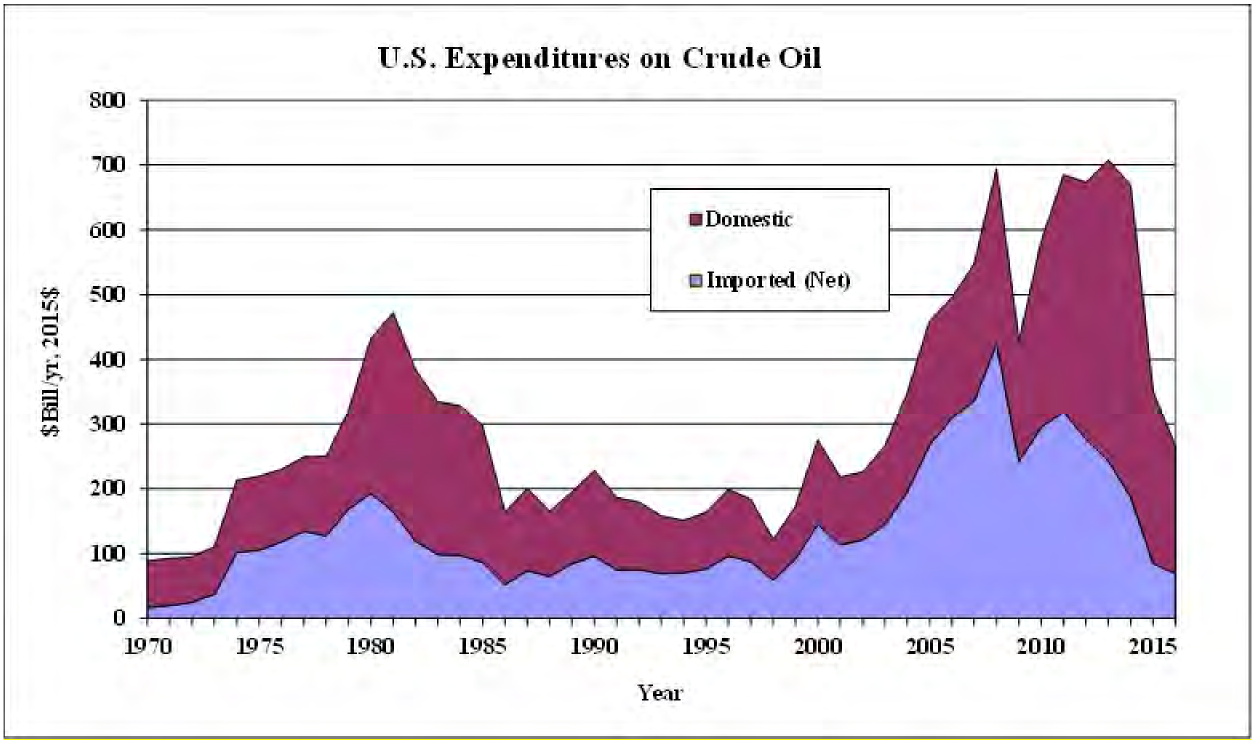


Figure 3.2 U.S. Expenditures on Crude Oil from 1970 through 2016[34]

Focusing on changes in oil import levels as a source of vulnerability has been standard practice in assessing energy security in the past, but given current market trends both from domestic and international levels, adding changes in consumption of petroleum to this assessment may provide better information about U.S. energy security. The major mechanism through which the economy sustains harm due to fluctuations in the world energy market is through price, which itself is leveraged through both imports and consumption. While the United States may be increasingly insulated from the physical effects of overseas oil disruptions, the price impacts of an oil disruption anywhere will continue to be transmitted to U.S. markets. As of 2015, Canada accounted for 43 percent of U.S. net oil imports of crude oil and petroleum products.[35] The implications of the U.S. becoming a significant petroleum producer have yet to be discerned in the literature, but it can be anticipated that this will have some impact on energy security.

In 2010, just over 40 percent of world oil supply came from OPEC nations. The AEO 2016 Reference Case[36] projects that this share will stay high and gradually rise; reaching 43 percent by 2020 and 45 percent by 2035 and thereafter. Approximately 32 percent of global supply is from Middle East and North African countries alone, a share that is also expected to grow over the long term. Measured in terms of the share of world oil resources or the share of global oil export supply, rather than oil production, the concentration of global petroleum resources in OPEC nations is even larger. As another measure of concentration, of the 137 countries/principalities that export either crude or refined products, the top 12 have accounted for, in recent years, between 55 and 70 percent of global exports.[37] Eight of these countries are members of OPEC, and a ninth is Russia.[K] In a market where even a 1–2 percent supply loss can raise prices noticeably, and where a 10 percent supply loss could lead to an unprecedented price shock, this regional concentration is of concern.[L] Historically, the countries of the Middle East have been the source of eight of the ten major world oil disruptions,[38] with the ninth originating in Venezuela, an OPEC country, and the tenth being Hurricanes Katrina and Rita.

EPA uses a processed combination of the MOVES and OMEGA models to estimate the reductions in U.S. fuel consumption due to the LDV GHG standards. Based on a detailed analysis of differences in U.S. fuel consumption, petroleum imports, and imports of petroleum products, the agency estimates that approximately 90 percent of the reduction in fuel consumption resulting from adopting improved GHG emission standards is likely to be reflected in reduced U.S. imports of crude oil and net imported petroleum products.[39] Thus, on balance, each gallon of fuel saved as a consequence of the LDV GHG standards is anticipated to reduce total U.S. imports of petroleum by 0.9 gallons. Based upon the fuel savings estimated by the models and the 90 percent oil import factor, the reduction in U.S. oil imports from the 2022–2025 LDV GHG standards are estimated for selected years from 2022 to 2050 (in millions of barrels per day (MMBD) in Table 3.10 below. For comparison purposes, Table 3.10 also shows U.S. oil exports/imports, U.S. net product imports and U.S. net crude/product imports in selected years from 2022 to 2040, as projected by DOE in the Annual Energy Outlook 2016 Reference Case. Real U.S. Gross Domestic Product (GDP) is projected to grow by 47 percent over the same time frame (e.g., from 2022 to 2040) in the AEO 2016 Reference projections. Real U.S. GDP is modestly lower in the AEO 2016 than in the AEO 2015 Reference projection. The AEO 2015 projects that real U.S. GDP will grow by 52 percent during that same time frame.

[K] The other three are Norway, Canada, and the EU, an exporter of product.

[L] For example, the 2005 Hurricanes Katrina/Rita and the 2011 Libyan conflict both led to a 1.8 percent reduction in global crude supply. While the price impact of the latter is not easily distinguished given the rapidly rising post-recession prices, the former event was associated with a 10-15 percent world oil price increase. There are a range of smaller events with smaller but noticeable impacts. Somewhat larger events, such as the 2002-2003 Venezuelan Strike and the War in Iraq, corresponded to about a 2.9 percent sustained loss of supply, and was associated with a 28 percent world oil price increase. Compiled from EIA oil price data, IEA2012 [IEA Response System for Oil Supply Emergencies (http://www.iea.org/publications/freepublications/publication/EPPD_Brochure_English_2012_02.pdf) [EPA-HQ-OAR-2014-0827-0573] See table on P. 11.and Hamilton 2011 "Historical Oil Shocks," (http://econweb.ucsd.edu/~jhamilto/oil_history.pdfin [EPA-HQ-OAR-2014-0827-0598] Routledge Handbook of Major Events in Economic History*, pp. 239-265, edited by Randall E. Parker and Robert Whaples, New York: Routledge Taylor and Francis Group, 2013).

Table 3.10 Projected Trends in U.S. Oil Exports/Imports, and U.S. Oil Import Reductions Resulting from the Program in Selected Years from 2022 to 2050, (Millions of barrels per day (MMBD)

Year	U.S. Oil Exports	U.S. Gross Oil Imports	U.S. Net Product Imports*	U.S. Net Crude & Product Imports	U.S. Reductions from Oil Imports
2022	0.63	7.56	-3.39	3.54	0.019
2023	0.63	7.57	-3.44	3.50	0.055
2024	0.63	7.57	-3.57	3.37	0.106
2025	0.63	7.58	-3.69	3.26	0.169
2030	0.63	7.20	-4.32	2.25	0.420
2035	0.83	7.07	-4.52	1.72	0.685
2040	1.02	7.12	-4.66	1.44	0.880
2050	**	**	**	**	1.119

Notes:
* Negative U.S. Net Product Imports imply positive exports.
**The AEO 2016 only projects energy market and economic trends through 2040.

3.5.2 Energy Security Implications

In order to understand the energy security implications of reducing U.S. oil imports, EPA has worked with Oak Ridge National Laboratory (ORNL), which has developed approaches for evaluating the social costs and energy security implications of oil use. The energy security estimates provided below are based upon a methodology developed in a peer-reviewed study entitled, "*The Energy Security Benefits of Reduced Oil Use, 2006-2015*," completed in March 2008. This ORNL study is an updated version of the approach used for estimating the energy security benefits of U.S. oil import reductions developed in a 1997 ORNL Report.[40] This approach has been used to estimate energy security benefits for the LDV GHG/fuel economy standards (2012–2016; 2017–2025) and the HDV GHG/fuel economy standards Phase I (2014–2018)/Phase II (2018 and later). For these rulemakings, the ORNL methodology is updated periodically to account for forecasts of future energy market and economic trends reported in the U.S. Energy Information Administration's (EIA) AEO. The agency continues to monitor the energy security literature for new information that could influence our energy security analysis.

When conducting this analysis, ORNL considered the full cost of importing petroleum into the U.S. The full economic cost is defined to include two components in addition to the purchase price of petroleum itself. These are: (1) the higher costs for oil imports resulting from the effect of U.S. demand on the world oil price (i.e., the "demand" or "monopsony" costs); and (2) the risk of reductions in U.S. economic output and disruption to the U.S. economy caused by sudden disruptions in the supply of imported oil to the U.S. (i.e., macroeconomic disruption/adjustment costs).

For this Proposed Determination, ORNL updated the energy security premiums by incorporating the most recent oil price forecast and energy market trends, particularly regional oil supplies and demands, from the AEO 2016 Reference Case into its model.[41] Below are

ORNL energy security premium estimates for the selected years from 2020 to 2050,[M] as well as a breakdown of the components of the energy security premiums for each year. The energy security premiums estimated for the Proposed Determination are lower than those estimated for the Draft TAR, because the values for the Proposed Determination are based upon the AEO 2016 Reference Case projections, which has slightly (4-5 percent) lower oil prices and significantly (18-44 percent) lower U.S. oil imports in 2030-2035 compared to the AEO 2015 Reference Case. The components of the energy security premiums and their values are discussed below.

Table 3.11 Energy Security Premiums in Selected Years from 2022 to 2050, (2015 $/Barrel)*

Year	Monopsony (Range)	Avoided Macroeconomic Disruption/Adjustment Costs (Range)	Total Mid-Point (Range)
2020	$2.92 ($0.66 - $3.65)	$5.48 ($2.64 - $8.93)	$8.40 ($4.97 - $12.13)
2025	$2.98 ($0.77 - $4.21)	$6.28 ($2.98 - $10.21)	$9.25 ($5.48 - $13.32)
2030	$2.07 ($0.84 - $4.64)	$6.89 ($3.06 - $11.16)	$8.94 ($5.22 - $12.98)
2035	$1.66 ($1.12 - $6.28)	$7.50 ($3.23 - $12.10)	$9.15 ($5.24 - $13.42)
2040	$1.52 ($1.21 - $6.29)	$8.08 ($3.41 - $13.04)	$9.59 ($5.41 - $14.19)
2045	$1.52 ($1.21 - $6.29)	$8.08 ($3.41 - $13.04)	$9.59 ($5.41 - $14.19)
2050	$1.52 ($1.21 - $6.29)	$8.08 ($3.41 - $13.04)	$9.59 ($5.41 - $14.19)

Note:
* The top values in each cell are the midpoints; the values in parentheses are the 90 percent confidence intervals.

3.5.2.1 Effect of Oil Use on the Long-Run Oil Price

The first component of the full economic costs of importing petroleum into the U.S. follows from the effect of U.S. import demand on the world oil price over the long-run. Because the U.S. is a sufficiently large purchaser of global oil supplies, its purchases can affect the world oil price. This monopsony power means that increases in U.S. petroleum demand can cause the world price of crude oil to rise, and conversely, that reduced U.S. petroleum demand can reduce the world price of crude oil. Thus, one benefit of decreasing U.S. oil purchases due to reductions in greenhouse gas emissions from light-duty vehicles is the potential decrease in the crude oil price paid for all crude oil purchased.

A variety of oil market and economic factors have contributed to lowering the estimated monopsony premium compared to monopsony premiums cited in previous 2017–2025 LDV GHG/fuel economy rulemakings. Three principal factors contribute to lowering the monopsony premium: lower world oil prices, lower U.S. oil imports, and less responsiveness of world oil prices to changes in U.S. oil demand. Below we consider differences in oil market trends by

[M] AEO 2016 forecasts energy market trends and values only to 2040. The post-2040 energy security premium values are assumed to be equal to the 2040 estimate.

comparing projections developed using the AEO 2012 (Early Release) and the AEO 2016. The AEO 2012 (Early Release) was used for the 2012 final LDV GHG/fuel economy rule and the AEO 2016 is being used for this Proposed Determination assessment, so the comparison gives a snapshot of how oil and energy markets have changed since the 2012 final rule.

The comparison shows a general downward revision in world oil price projections (e.g., a 31 percent reduction in 2025) and a reduction in projected U.S. oil imports due to increased U.S. supply (i.e., a 52 percent reduction in 2025) from the AEO 2012 (Early Release) to the AEO 2016. Based upon the AEO 2016 projections over the longer term and as the world oil price recovers, total U.S. imports are projected to gradually decrease and be 72 percent below the AEO 2012 (Early Release) projected level in 2035. The 72 percent reduction figure using the AEO 2016 Reference Case shows lower U.S. oil imports than if the AEO 2015 Reference Case is used. For the AEO 2015, U.S. oil imports only decline by 50 percent compared to the AEO 2012 (Early Release). The AEO 2016 Reference Case estimates of U.S. oil imports are lower than the AEO 2015 Reference Case estimates because the U.S. is producing more oil and thereby importing less oil over the AEO time frame. Projected U.S. oil demand in the AEO 2016 is little changed (within 2 percent) of the AEO 2015 projections through 2035.

Currently some OPEC countries (e.g., Saudi Arabia) are increasing oil supply in an attempt to price more expensive marginal suppliers, like the U.S., out of the market and regain market share, exacerbating the worldwide oil supply glut which has resulted in lowering the world oil price further. Lower world oil prices currently may reduce both production from existing domestic oil resources and investment in new domestic oil sources increasing U.S. oil import levels in the intermediate term.

Another factor influencing the monopsony premium is that U.S. demand on the global oil market is projected to decline, suggesting diminished overall influence and some reduction in the influence of U.S. oil demand on the world price of oil. This is a result of the U.S. being a smaller fraction of total world oil demand. Outside of the U.S., projected OPEC supply in the AEO 2016 remains roughly steady as a share of world oil supply compared to the AEO 2012 (Early Release). OPEC's share of world oil supply outside of the U.S. actually increases slightly over the long term. Since OPEC supply is estimated to be more price sensitive than non-OPEC supply, this high OPEC share means that AEO 2016 projected world oil supply is slightly more responsive to changes in U.S. oil demand. Together, these factors suggest that changes in U.S. oil import reductions have a somewhat smaller effect on the long-run world oil price than changes based on AEO 2012 (Early Release) estimates.

These changes in oil price and import levels lower the monopsony portion of energy security premium since this portion of the security premium is related to the change in total U.S. oil import costs that is achieved by a marginal reduction in U.S oil imports. Since both the price and the quantity of oil imports are lower, the monopsony premium component estimated in this assessment is 70-80 percent lower over the years 2025–2040 than the estimates based upon the AEO 2012 (Early Release) projections.

The literature on the energy security for the last two decades has routinely combined the monopsony and the macroeconomic disruption components when calculating the total value of the energy security premium. However, in the context of using a global value for the Social Cost of Carbon (SCC) the question arises: how should the energy security premium be used when some benefits from the rule, such as the benefits of reducing greenhouse gas emissions, are calculated from a global perspective? Monopsony benefits represent avoided payments by U.S. consumers to oil producers that result from a decrease in the world oil price as the U.S. decreases its demand for oil. Although there is clearly an overall benefit to the U.S. when considered from a domestic perspective, the decrease in price due to decreased demand in the U.S. also represents a loss to oil producing countries, one of which is the U.S.

Given the redistributive nature of this monopsony effect from a global perspective, it has been excluded in the energy security benefits calculations in past rulemakings. In contrast, the other portion of the energy security premium, the avoided U.S. macroeconomic disruption and adjustment cost that arises from reductions in U.S. petroleum imports, does not have offsetting impacts outside of the U.S., and, thus, is included in the energy security benefits. To summarize, the agency has included only the avoided macroeconomic disruption portion of the energy security benefits to estimate the monetary value of the total energy security benefits.

There is disagreement in the literature about the magnitude of the monopsony component, and its relevance for policy analysis. Brown and Huntington (2013)[42], for example, argue that the U.S.'s refusal to exercise its market power to reduce the world oil price does not represent a proper externality, and that the monopsony component should not be considered in calculations of the energy security externality. However, they also note in their earlier discussion paper (Brown and Huntington 2010)[43] that this is a departure from the traditional energy security literature, which includes sustained wealth transfers associated with stable but higher-price oil markets.

On the other hand, Greene (2010)[44] and others in prior literature (e.g., Toman 1993)[45] have emphasized that the monopsony cost component is policy-relevant because the world oil market is non-competitive and strongly influenced by cartelized and government-controlled supply decisions. Thus, while sometimes couched as an externality, Greene notes that the monopsony component is best viewed as stemming from a completely different market failure than an externality (Ledyard 2008),[46] yet still implying marginal social costs to importers.

The Council on Foreign Relations[47] (Council (2015)) released a discussion paper that assesses NHTSA's analysis of the benefits and costs of CAFE in a lower-oil-price world. In this paper, the Council notes that while NHTSA cites the monopsony effect of the CAFE standards for 2017–2025, NHTSA does not include it when calculating the cost-benefit calculation for the rule. The Council argues that the monopsony benefit should be included in the CAFE cost-benefit analysis and that including the monopsony benefit is more consistent with the legislators' intent in mandating CAFE standards in the first place. The same comment the Council raised about NHTSA's CAFE standards would apply to these GHG vehicle standards.

The National Academy of Sciences (NAS (2015)) Report, "Cost, Effectiveness and the Deployment of Fuel Economy Technologies for Light-Duty Vehicles,"[48] suggests that the agency's logic about not accounting for monopsony benefits is inaccurate. According to the NAS, the fallacy lies in treating the two problems, oil dependence and climate change, similarly. According to the NAS, "Like national defense, it [oil dependence] is inherently adversarial (i.e., oil consumers against producers using monopoly power to raise prices). The problem of climate change is inherently global and requires global action. If each nation considered only the benefits to itself in determining what actions to take to mitigate climate change, an adequate solution could not be achieved. Likewise, if the U.S. considers the economic harm its reduced petroleum use will do to monopolistic oil producers it will not adequately address its oil dependence problem. Thus, if the United States is to solve both of these problems it must take full account of the costs and benefits of each, using the appropriate scope for each problem." Based upon the assessment of the monopsony premium in the Council of Foreign Relations and NAS reports, we sought public input in the Draft TAR on whether it is appropriate to consider monopsony in the societal costs/benefits of the National Program but received no comments.

There is also a question about the ability of gradual, long-term reductions, such as those resulting from the LDV GHG standards, to reduce the world oil price in the presence of OPEC's monopoly power. OPEC is currently the world's marginal petroleum supplier, and could conceivably respond to gradual reductions in U.S. demand with gradual reductions in supply over the course of several years as the fuel savings resulting from this program grow. However, if OPEC opts for a long-term strategy to preserve its market share, rather than maintain a particular price level (as they have done recently in response to increasing U.S. petroleum production) reduced demand would create downward pressure on the global price. The Oak Ridge analysis assumes that OPEC does respond to demand reductions by reducing its supply over the long run, but there is still a price effect in the model because the supply reduction only partially offsets the demand reduction, enough to maintain supply share. Under the mid-case behavioral assumption used in the premium calculations, OPEC responds by gradually reducing supply to maintain *market share* (consistent with the long-term self-interested strategy suggested by Gately (2004, 2007)).[49]

It is important to note that the decrease in global petroleum prices resulting from these GHG standards could spur increased consumption of petroleum in other sectors and countries, leading to a modest uptick in GHG emissions outside of the U.S. This increase in global fuel consumption could offset some portion of the GHG reduction benefits associated with these standards. The agency has not quantified this increase in global oil consumption or GHG emissions outside the U.S. due to world oil price changes resulting from the standards. Recent research has quantified this type of effect in the context of biofuel policies (e.g., Drabik and de Gorter (2011);[50] Rajagopal, Hochman and Zilberman (2011);[51] Thompson, Whistance, and Meyer (2011)),[52] pipeline construction (Erickson and Lazarus (2014)),[53] and fuel economy policies (Karplus et al., (2015)).[54]

Quantifying resulting GHG emissions may be challenging because other fuels, with varying GHG intensities, could be displaced from the increasing use of oil worldwide, particularly outside of the transportation sector. For example, if a decline in the world oil price causes an increase in oil use in China, India, or another country's industrial sector, this increase in oil consumption may displace natural gas usage. Alternatively, the increased oil use could result in a decrease in coal used to produce electricity. We sought comment in the Draft TAR on whether there are robust methodologies that could be used to estimate world-wide changes in oil consumption and GHG emission impacts in the societal cost/benefit analysis of the National Program but received no comments.

3.5.2.2 Macroeconomic Disruption Adjustment Costs

The second component of the oil import premium, "avoided macroeconomic disruption/adjustment costs," arises from the effect of oil imports on the expected cost of supply disruptions and accompanying price increases. A sudden increase in oil prices triggered by a disruption in world oil supplies has two main effects: (1) it increases the costs of oil imports in the short-run and (2) it can lead to macroeconomic contraction, dislocation and Gross Domestic

Product (GDP) losses. For example, for the Proposed Determination, ORNL estimates the combined value of these two factors to be $6.28/barrel when U.S. oil imports are reduced in 2025, with a range from $2.98/barrel to $10.21/barrel of imported oil reduced, which are consistent with the values estimated in the Draft TAR. For the Draft TAR, the avoided macroeconomic disruption/adjustment costs with U.S. oil imports reductions in 2025 were $6.30/barrel with a range of $2.92/barrel to $10.22/barrel (2013$).

Since future disruptions in foreign oil supplies are an uncertain prospect, each of the disruption cost components must be weighted by the probability that the supply of petroleum to the U.S. will actually be disrupted. Thus, the "expected value" of these costs – the product of the probability that a supply disruption will occur and the sum of costs from reduced economic output and the economy's abrupt adjustment to sharply higher petroleum prices – is the relevant measure of their magnitude. Further, when assessing the energy security value of a policy to reduce oil use, it is only the change in the expected costs of disruption that results from the policy that is relevant. The expected costs of disruption may change from lowering the normal (i.e., pre-disruption) level of domestic petroleum use and imports, from any induced alteration in the likelihood or size of disruption, or from altering the short-run flexibility (e.g., elasticity) of petroleum use.

With updated oil market and economic factors, the avoided macroeconomic disruption component of the energy security over time is somewhat lower compared to the avoided macroeconomic disruption premiums used in the 2017–2025 LDV GHG/fuel economy rule (based upon the AEO 2012 (Early Release) and the Draft TAR (based upon the AEO 2015). Factors that contribute to moderately lowering the avoided macroeconomic disruption component are lower U.S. imports (reducing the global reliance on unstable supplies, and slightly diminishing the marginal effect of further U.S. imports reduction on global supply stability), lower real oil prices and slightly smaller price increases during prospective shocks. Real oil price levels in the AEO 2016 are 6-31 percent lower over the 2025–2040 period than the AEO 2012 (Early Release), and the likely increase in oil prices in the event of an oil shock are somewhat smaller, reflecting small increases in the responsiveness of global oil supply to changes in the world price of oil. Over the 2025–2040 period AEO 2016 projects domestic oil demand, and real GDP levels, are not significantly changed from AEO 2012 (Early Release) and from the Draft TAR. Oil demand is within 2 percent and GDP is within zero to 4 percent lower. So oil remains an important input to the U.S. economy. Overall, the avoided macroeconomic disruption component estimates for the oil security premiums are 26-29 percent lower over the period from 2025–2040 based upon different projected oil market and economic trends in the AEO 2016 compared to the AEO 2012 (Early Release). Compared to the Draft TAR, the avoided macroeconomic disruption component estimates for the oil security premiums are 4–28 percent lower over the period from 2025–2040 based upon different projected oil market and economic trends in the AEO 2015 compared to the AEO 2012 (Early Release).

There are several reasons why the avoided macroeconomic disruption premiums changed only moderately. One reason is that the projected macroeconomic sensitivity to oil price shocks is held unchanged from the historical average levels used in multiple prior estimates, since projected U.S. oil consumption levels and the expenditures on oil in the U.S. economy remain at comparatively high levels under both AEO 2012 (Early Release) and AEO 2016. Figure 3.3 below shows that under AEO 2016, projected U.S. real annual oil expenditures continue to rise after 2016 from under $300 billion to over $820 billion (2015$) by 2035. The value share of

U.S. oil use, labeled in the figure below as U.S. oil expenditures as share of GDP, remains at roughly three percent after 2020 even as the economy grows, lower than the AEO 2012 (Early Release) projection of 4.4 percent declining to 3.6 percent. The value share of oil use in the AEO 2016 is still projected to be above the full historical average (2.8 percent for 1970–2010), and well above the historical levels observed from 1985 to 2005 (1.9 percent). A second factor is that oil disruption risks are little changed. The two factors influencing disruption risks are the probability of global supply interruptions and the world oil supply share from OPEC. Both factors are not significantly different from previous forecasts of oil market trends.

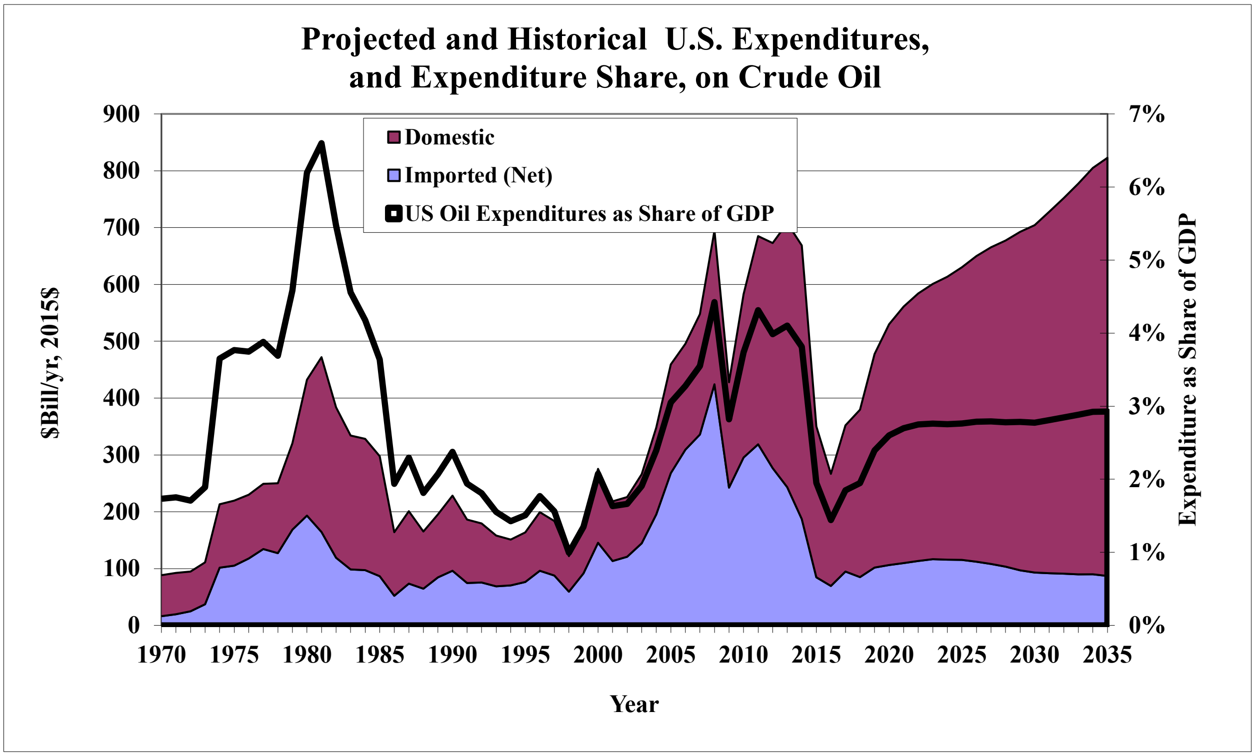


Figure 3.3 Projected and Historical U.S. Expenditures, and Expenditure Share, on Crude Oil[55]

The energy security costs estimated here follow the oil security premium framework, which is well-established in the energy economics literature. The oil import premium gained attention as a guiding concept for energy policy around the time of the second and third major post-war oil shocks. Bohi and Montgomery (1982), EMF (1982)[56], Plummer (1982)[57] provided valuable discussion of many of the key issues related to the oil import premium as well as the analogous oil stockpiling premium. Bohi and Montgomery (1982)[58] detailed the theoretical foundations of the oil import premium and established many of the critical analytic relationships through their thoughtful analysis. Hogan (1981)[59] and Broadman and Hogan (1986, 1988)[60] revised and extended the established analytical framework to estimate optimal oil import premium with a more detailed accounting of macroeconomic effects.

Since the original work on energy security was undertaken in the 1980's, there have been several reviews on this topic. For example, Leiby, Jones, Curlee and Lee (1997)[61] provided an extended review of the literature and issues regarding the estimation of the premium. Parry and

Darmstadter (2004)[62] also provided an overview of extant oil security premium estimates and estimated some premium components.

The recent economics literature on whether oil shocks are the threat to economic stability that they once were is mixed. Some of the current literature asserts that the macroeconomic component of the energy security externality is small. For example, the National Research Council (2009) argued that the non-environmental externalities associated with dependence on foreign oil are small, and potentially trivial.[63] Analyses by Nordhaus (2007) and Blanchard and Gali (2010) question the impact of more recent oil price shocks on the economy.[64] They were motivated by attempts to explain why the economy actually expanded immediately after the oil shocks in the early 2000 time frame, and why there was no evidence of higher energy prices being passed on through higher wage inflation. Using different methodologies, they conclude that the economy is less sensitive to dramatic swings in oil prices.

One reason, according to Nordhaus, is that monetary policy has become more accommodating to the price impacts of oil shocks. Another is that consumers have simply decided that such movements are temporary, and have noted that price impacts are not passed on as inflation in other parts of the economy. He also notes that real changes to productivity due to oil price increases are incredibly modest,[N] and that the general direction of the economy matters a great deal regarding how the economy responds to a shock. Estimates of the impact of a price shock on aggregate demand are insignificantly different from zero.

Blanchard and Gali (2010) contend that improvements in monetary policy (as noted above), more flexible labor markets, and lessening of energy intensity in the economy, combined with an absence of concurrent shocks, all contributed to lessen the impact of oil shocks after 1980. They find "… the effects of oil price shocks have changed over time, with steadily smaller effects on prices and wages, as well as on output and employment."[65] In a comment at the chapter's end, this work is summarized as follows: "The message of this chapter is thus optimistic in that it suggests a transformation in U.S. institutions has inoculated the economy against the responses that we saw in the past."

At the same time, the implications of the "shale oil revolution" are now being felt in the international markets, with current prices remain fairly low. Analysts generally attribute this result in part to the significant increase in supply resulting from U.S. production, which has put liquid petroleum production roughly on par with Saudi Arabia. The price decline is also attributed to the sustained reductions in U.S. consumption and global demand growth from fuel efficiency policies and previously high oil prices. The resulting decrease in foreign imports, down to about one-third of domestic consumption (from 60 percent in 2005, for example[66]), effectively permits U.S. supply to act as a buffer against artificial or other supply restrictions (the latter due to conflict or a natural disaster, for example).

However, other papers suggest that oil shocks, particularly sudden supply shocks, remain a concern. Both Blanchard and Gali's and Nordhaus work were based on data and analysis through 2006, ending with a period of strong global economic growth and growing global oil

[N] In fact, "… energy-price changes have no effect on multifactor productivity and very little effect on labor productivity." Page 19. He calculates the productivity effect of a doubling of oil prices as a decrease of 0.11 percent for one year and 0.04 percent a year for ten years. Page 5. (The doubling reflects the historical experience of the post-war shocks, as described in Table 7.1 in Blanchard and Gali, pp. 380) demand. The Nordhaus work particularly stressed the effects of the price increase from 2002–2006 that were comparatively gradual (about half the growth rate of the 1973 event and one-third that of the 1990 event). The Nordhaus study emphasizes the robustness of the U.S. economy during a time period through 2006. This time period was just before rapid further increases in the price of oil and other commodities with oil prices more-than-doubling to over $130/barrel by mid-2008, only to drop after the onset of the largest recession since the Great Depression in the U.S.

Hamilton (2012)[67] reviewed the empirical literature on oil shocks and suggested that the results are mixed, noting that some work (e.g. Rasmussen and Roitman (2011) finds less evidence for economic effects of oil shocks, or declining effects of shocks (Blanchard and Gali 2010), while other work continues to find evidence regarding the economic importance of oil shocks. For example, Baumeister and Peersman (2011) found that an oil price increase had a decreasing effect over time. But they note that with a declining price-elasticity of demand that a given physical oil disruption would have a bigger effect on price and a similar effect on output as in the earlier data. Hamilton observes that "a negative effect of oil prices on real output has also been reported for a number of other countries, particularly when nonlinear functional forms have been employed." Alternatively, rather than a declining effect, Ramey and Vine (2010) found "remarkable stability in the response of aggregate real variables to oil shocks once we account for the extra costs imposed on the economy in the 1970s by price controls and a complex system of entitlements that led to some rationing and shortages."[68]

Some of the recent literature on oil price shocks has emphasized that economic impacts depend on the nature of the oil shock, with differences between price increases caused by sudden supply loss and those caused by rapidly growing demand. Most recent analyses of oil price shocks have confirmed that "demand-driven" oil price shocks have greater effects on oil prices and tend to have positive effects on the economy while "supply-driven" oil shocks still have negative economic impacts (Baumeister, Peersman and Van Robays (2010)).[69] A recent paper by Kilian and Vigfusson (2014)[70], for example, assigned a more prominent role to the effects of price increases that are unusual, in the sense of being beyond range of recent experience. Kilian and Vigfusson also conclude that the difference in response to oil shocks may well stem from the different effects of demand- and supply-based price increases: "One explanation is that oil price shocks are associated with a range of oil demand and oil supply shocks, some of which stimulate the U.S. economy in the short run and some of which slow down U.S. growth (see Kilian (2009)). How recessionary the response to an oil price shock is thus depends on the average composition of oil demand and oil supply shocks over the sample period."

The general conclusion that oil supply-driven shocks reduce economic output is also reached in a paper by Cashin et al. (2014)[71] for 38 countries from 1979-2011. "The results indicate that the economic consequences of a supply-driven oil-price shock are very different from those of an oil-demand shock driven by global economic activity, and vary for oil-importing countries compared to energy exporters," and "oil importers [including the U.S.] typically face a long-lived fall in economic activity in response to a supply-driven surge in oil prices" but almost all countries see an increase in real output for an oil-demand disturbance. Note that the energy security premium calculation in this analysis is based on price shocks from potential future supply events only.

By early 2015, world oil prices were sharply lower than in 2014. Future prices remain uncertain, but sustained markedly lower oil prices can have mixed implications for U.S. energy security. Under lower prices U.S. expenditures on oil consumption are lower, and the expenditures are a less prominent component of the U.S. economy. But sustained lower oil prices encourage greater oil consumption, and reduce the competitiveness of new U.S. oil supplies and alternative fuels. The AEO 2016 low-oil price outlook, for example, projects that by 2030 total U.S. petroleum supply would be 29 percent lower and net imports would be 204 percent higher than the AEO 2016 Reference Case. Under the low-price case, 2030 crude prices are 56 percent lower, while net imports of crude and product increase from 2.2 MMBD to 6.8 MMBD so that U.S. net import expenditures are 33 percent higher.[O]

A second potential proposed energy security effect of lower oil prices is increased instability of supply, due to greater global reliance on fewer suppling nations,[P] and because lower prices may increase economic and geopolitical instability in some supplier nations.[72,73,74] The International Monetary Fund reported that low oil prices are creating substantial economic tension for Middle East oil producers on top of the economic costs of ongoing geopolitical conflicts, and noted the risk that Middle East countries including Saudi Arabia could run out of financial assets without a substantial change in policy.[75] The concern raised is that oil revenues are essential for some exporting nations to fund domestic programs and avoid domestic unrest.

Finally, despite continuing uncertainty about oil market behavior and outcomes and the sensitivity of the U.S. economy to oil shocks, it is generally agreed that it is beneficial to reduce petroleum fuel consumption from an energy security standpoint. It is not just imports alone, but both imports and consumption of petroleum from all sources and their role in economic activity, that may expose the U.S. to risk from price shocks in the world oil price. Reducing fuel consumption reduces the amount of domestic economic activity associated with a commodity whose price depends on volatile international markets. The relative significance of petroleum consumption and import levels for the macroeconomic disturbances that follow from oil price shocks is not fully understood. Recognizing that changing petroleum consumption will change U.S. imports, this assessment of oil costs focuses on those incremental social costs that follow from the resulting changes in imports, employing the usual oil import premium measure.

3.5.2.3 Cost of Existing U.S. Energy Security Policies

The last often-identified component of the full economic costs of U.S. oil imports are the costs to the U.S. taxpayers of existing U.S. energy security policies. The two primary examples are maintaining the Strategic Petroleum Reserve (SPR) and maintaining a military presence to

---

[O] For simplicity and given available data, this computation treats net import expenditures as proportional to net import volumes. For the low-oil price case net petroleum imports in 2030 are 4.6 MMBD greater than in the Reference case, primarily due to a large reduction in product exports (4.1 MMBD smaller), and a smaller (0.5 MMDB) increase in crude imports. Since the import change is primarily due to a loss of the more highly-priced product exports, the expenditure change could be larger.

[P] Fatih Birol, Executive Director of the International Energy Agency, warns that prolonged lower oil prices would trigger energy-security concerns by increasing reliance on a small number of low-cost producers "or risk a sharp rebound in price if investment falls short." "It would be a grave mistake to index our attention to energy security to changes in the oil price," Birol said. "Now is not the time to relax. Quite the opposite: a period of low oil prices is the moment to reinforce our capacity to deal with future energy security threats." International Energy Agency, World Energy Outlook, November 10th, 2015.

help secure a stable oil supply from potentially vulnerable regions of the world. The SPR is the largest stockpile of government-owned emergency crude oil in the world. Established in the aftermath of the 1973/1974 oil embargo, the SPR provides the U.S. with a response option should a disruption in commercial oil supplies threaten the U.S. economy. It also allows the U.S. to meet part of its International Energy Agency obligation to maintain emergency oil stocks, and it provides a national defense fuel reserve. While the costs for building and maintaining the SPR are more clearly related to U.S. oil use and imports, historically these costs have not varied in response to changes in U.S. oil import levels. Thus, while the effect of the SPR in moderating price shocks is factored into the ORNL analysis, the cost of maintaining the SPR is excluded.

3.5.2.4 Military Security Cost Components of Energy Security

The agency has also attempted to assess the military security benefits components of energy security in past LDV rulemakings and the Draft TAR. The recent literature on the military components of energy security has included three broad categories of oil related military and national security costs all of which are hard to quantify and provide estimates of their costs. These include possible costs of U.S. military programs to secure oil supplies from unstable regions of the world, the energy security costs associated with the U.S. military's reliance on petroleum to fuel its operations and possible national security costs associated with expanded oil revenues to "rogue states."

Of these categories listed above, the one that is most clearly connected to petroleum use and is, in principle, quantifiable is the first, the cost of military programs to secure oil supplies and stabilize oil supplying regions. There is a developing literature on the measurement of these components of energy security but methodological and measurement challenges pose significant challenges to providing a robust estimate of this component of energy security.

Assessing the military component of the energy security cost has two major challenges: attribution and incremental analysis. The attribution challenge is to determine which military programs and expenditures can properly be attributed to oil supply protection, rather than some other national security objective. The incremental analysis challenge is to estimate how much the petroleum supply protection costs might vary if U.S. oil use were to be reduced or eliminated.

Since "military forces are, to a great extent, multipurpose and fungible" across theaters and missions (Crane et al. (2009))[76], and because the military budget is presented along regional accounts rather than by mission, the allocation to particular missions is not always clear. Approaches taken usually either allocate "partial" military costs directly associated with operations in a particular region, or allocate a share of total military costs (including some that are indirect in the sense of supporting military activities overall) (Koplow and Martin (1998)).[77]

The incremental analysis can estimate how military costs would vary if the oil security mission is no longer needed, and many studies stop at this point. It is substantially more difficult to estimate how military costs would vary if U.S. oil use or imports are partially reduced. Partial reduction of U.S. oil use diminishes the magnitude of the security problem, but there is uncertainty that supply protection forces and their costs could be scaled down in proportion (e.g. Crane et al. (2009))[78], and there remains the associated goal of protecting supply and transit for allies and important trade partners, and other importing countries, if they do not decrease their petroleum use as well.

The challenges of attribution and incremental analysis have led some to conclude that the mission of oil supply protection cannot be clearly separated from others, and the military cost component of oil security should be taken as near zero (Moore et al. (1997)).[79] For example, the Council on Foreign Relations takes the view that substantial foreign policy missions will remain over the next 20 years, even without the oil security mission entirely. Stern, on the other hand, argues that many of the other policy concerns in the Persian Gulf follow from oil, and the reaction to U.S. policies taken to protect oil.

Most commonly, analysts estimate substantial military costs associated with the missions of oil supply security and associated contingencies, but avoid estimating specific cost reductions from partial reductions in oil use. However, some studies (Copulos (2003), Delucchi and Murphy (2008), Crane et al., Stern (2010))[80] seek to update, and in some cases significantly improve the rigor of analysis.

Delucchi and Murphy sought to deduct from the cost of Persian Gulf military programs, the costs associated with defending U.S. interests other than the objective of providing more stable oil supply and price to the U.S. economy. Excluding an estimate of cost for missions unrelated to oil, and for the protection of oil in the interest of other countries, Delucchi and Murphy estimated military costs for all U.S. domestic oil interests of between $24 and $74 billion annually.

Crane et al. considered force reductions and cost savings that could be achieved if oil security were no longer a consideration. After reviewing documents supporting recent defense resource allocations, they concluded that the oil protection mission is prominent: “First, the United States does include the security of oil supplies and global transit of oil as a prominent element in its force planning.” While they noted that the elimination of this mission of oil supply protection might not lead to complete reduction of those costs, they concluded there is very likely to be some cost reduction. Taking two approaches, and guided by post-Cold War force draw downs and by a top-down look at the current U.S. allocation of defense resources, they concluded that $75–$91 billion, or 12–15 percent of the current U.S. defense budget, could be reduced if the oil protection mission were completely eliminated.

Stern presents an estimate of military cost for Persian Gulf force projection, addressing the challenge of cost allocation with an activity-based cost method. He used information on actual naval force deployments rather than budgets, focusing on the costs of carrier deployment. As a result of this different data set and these assumptions regarding allocation, the estimated costs are much higher, roughly 4 to 10 times, than other recent estimates. For the 1976–2007 time frame, Stern estimated an average military cost of $212 billion and for 2007, $500 billion.

A study by the National Research Council (NRC) (2013)[81] attempted to estimate the military costs associated with U.S. imports and consumption of petroleum. The NRC cites estimates of the national defense costs of oil dependence from the literature that range from less than $5 billion to $50 billion per year or more. Assuming an approximate range of $10–$50 billion per year, the NRC divided national defense costs by a projected U.S. consumption rate of approximately 6.4 billion barrels per year (EIA, 2012). This procedure yielded a range of average national defense cost of $1.50–$8.00 per barrel (rounded to the nearest $0.50), with a mid-point of $5/barrel (in 2009$). However, as discussed above, it is unclear that incremental reductions in either U.S. imports, or consumption of domestic petroleum, would produce incremental changes to the military expenditures related to the oil protection mission (Crane, et al.). We did not receive any comments on this issue in the Draft TAR.

3.6 Non-GHG Health and Environmental Impacts

This section discusses the economic benefits from reductions in health and environmental impacts resulting from non-GHG emission reductions (such as criteria and toxic air pollutants) that can be expected to occur as a result of the light-duty 2022-2025 GHG standards. CO_2 emissions are predominantly the byproduct of fossil fuel combustion processes that also produce criteria and hazardous air pollutant emissions. The vehicles that are subject to this program are also significant sources of mobile source air pollution such as directly emitted Particulate Matter (PM), Nitrogen Oxide (NO_X), Volatile Organic Chemicals (VOCs) and air toxics, which are regulated by separate emissions standards programs. The program will affect exhaust emissions of these pollutants from vehicles and will also affect emissions from upstream sources that occur during the refining and distribution of fuel. Changes in ambient concentrations of ozone, $PM_{2.5}$, and air toxics that will result from the program are expected to affect human health by reducing premature deaths and other serious human health effects, as well as other important improvements in public health and welfare. Children especially benefit from reduced exposures to criteria and toxic pollutants, because they tend to be more sensitive to the effects of these respiratory pollutants. Ozone and particulate matter have been associated with increased asthma exacerbation and other respiratory effects in children, and particulate matter has been associated with deficits in lung function development.

It is important to quantify the co-pollutant-related health and environmental impacts associated with the GHG standards because a failure to adequately consider these ancillary impacts could lead to an incorrect assessment of the standards' costs and benefits. Moreover, the health and other impacts of exposure to criteria air pollutants and airborne toxics tend to occur in the near term, while most effects from reduced climate change are likely to occur only over a time frame of several decades or longer.

For purposes of this Proposed Determination, EPA has applied PM-related benefits per-ton values to its estimated emission reductions to estimate only the PM-related benefits of the program.[82,Q] However, there are several health benefit categories that EPA was unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. For example, we have not quantified a number of known or suspected health benefits linked to reductions in ozone and other criteria pollutants, as well as health benefits linked to reductions in air toxics. Additionally, we are unable to quantify a number of known welfare effects, including reduced acid and particulate deposition damage to cultural monuments and other materials, and environmental benefits due to reductions of impacts of eutrophication in coastal areas. As a result, the health benefits quantified in this analysis are likely underestimates of total benefits.

[Q] See also: http://www.epa.gov/airquality/benmap/sabpt.html. The current values available on the webpage have been updated since the publication of the Fann et al., 2012 paper. For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed June 9, 2016).

3.6.1 Economic Value of Reductions in Particulate Matter

As presented in Appendix C of the Proposed Determination document, the standards would reduce emissions of several criteria and toxic pollutants and their precursors. In this analysis, however, EPA only estimates the economic value of the human health benefits associated with the resulting reductions in $PM_{2.5}$ exposure (related to both directly emitted $PM_{2.5}$ and secondarily-formed $PM_{2.5}$). Due to analytical limitations with the benefit per-ton method, this analysis does not estimate benefits resulting from reductions in population exposure to other criteria pollutants such as ozone.[R] Furthermore, the benefits per-ton method, like all air quality impact analyses, does not monetize all of the potential health and welfare effects associated with reduced concentrations of $PM_{2.5}$.

This analysis uses estimates of the benefits from reducing the incidence of the specific $PM_{2.5}$-related health impacts described below. These estimates, which are expressed per ton of $PM_{2.5}$-related emissions eliminated by the standards, represent the total monetized value of human health benefits (including reduction in both premature mortality and premature morbidity) from reducing each ton of directly emitted $PM_{2.5}$, or its precursors (SO_2 and NO_X), from a specified source.

The PM-related dollar-per-ton benefit estimates used in this analysis, which are consistent with those used in the Draft TAR, are provided in Table 3.12. As the table indicates, these values differ among directly emitted PM and PM precursors (SO_2 and NO_X), and also depend on their original source, because emissions from different sources can result in different degrees of population exposure and resulting health impacts. In the summary of costs and benefits, Chapter 5, EPA presents the monetized value of total PM-related improvements associated with the standards summed across sources (on-road and upstream) sources and across PM-related pollutants (direct $PM_{2.5}$ and PM precursors SO_2 and NO_X).

Table 3.12 PM-Related Benefits-per-ton Values (thousands, 2012$)[a]

Year[c]	On-road Mobile Sources			Upstream Sources[d]		
	Direct $PM_{2.5}$	SO_2	NO_X	Direct $PM_{2.5}$	SO_2	NO_X
Estimated Using a 3 Percent Discount Rate[b]						
2022	$400-$910	$22-$49	$8.1-$18	$350-$790	$75-$170	$7.4-$17
2025	$440-$1,000	$24-$55	$8.8-$20	$390-$870	$83-$190	$8.1-$18
2030	$480-$1,100	$27-$61	$9.6-$22	$420-$950	$91-$200	$8.7-$20
Estimated Using a 7 Percent Discount Rate[b]						
2022	$370-$820	$20-$44	$7.4-$17	$320-$720	$67-$150	$6.6-$15
2025	$400-$910	$22-$49	$8.0-$18	$350-$790	$75-$170	$7.3-$17
2030	$430-$980	$24-$55	$8.6-$20	$380-$850	$81-$180	$7.9-$18

Notes:
[a] The benefit-per-ton estimates presented in this table are based on a range of premature mortality estimates derived from the ACS study (Krewski et al., 2009) and the Six-Cities study (Lepeule et al., 2012).
[b] The benefit-per-ton estimates presented in this table assume either a 3 percent or 7 percent discount rate in the valuation of premature mortality to account for a twenty-year segmented cessation lag.

[R] The air quality modeling that underlies the PM-related benefit per ton values also produced estimates of ozone levels attributable to each sector. However, the complex non-linear chemistry governing ozone formation prevented EPA from developing a complementary array of ozone benefit per ton values. This limitation notwithstanding, we anticipate that the ozone-related benefits associated with reducing emissions of NO_X and VOC could be substantial.

[c] Benefit-per-ton values were estimated for the years 2020, 2025 and 2030. We hold values constant for intervening years (e.g., 2020 values for years 2021-2024; 2025 values for years 2026-2029; and 2030 values for years 2031 and beyond).
[d] We assume for the purpose of this analysis that "upstream emissions" are most closely associated with refinery sector benefit per-ton values. The majority of upstream emission reductions associated with the standards are related to domestic onsite refinery emissions and domestic crude production. While upstream emissions also include storage and transport sources, as well as upstream refinery sources, we have chosen to simply apply the refinery values.

The benefit per-ton technique has been used in previous analyses, including EPA's Heavy-Duty Vehicle GHG standards Phase II (2018 and later),[83] 2017-2025 Light-Duty Vehicle Greenhouse Gas Rule,[84] the Reciprocating Internal Combustion Engine rules,[85,86] and the Residential Wood Heaters NSPS.[87] Table 3.13 shows the quantified $PM_{2.5}$-related co-benefits captured in those benefit per-ton estimates, as well as unquantified effects the benefits per-ton estimates are unable to capture.

Table 3.13 Human Health and Welfare Effects of $PM_{2.5}$

Pollutant	Quantified and Monetized in Primary Estimates	Unquantified Effects Changes in:
$PM_{2.5}$	Adult premature mortality Acute bronchitis Hospital admissions: respiratory and cardiovascular Emergency room visits for asthma Nonfatal heart attacks (myocardial infarction) Lower and upper respiratory illness Minor restricted-activity days Work loss days Asthma exacerbations (asthmatic population) Infant mortality	Chronic and subchronic bronchitis cases Strokes and cerebrovascular disease Low birth weight Pulmonary function Chronic respiratory diseases other than chronic bronchitis Non-asthma respiratory emergency room visits Visibility Household soiling

Readers interested in reviewing the complete methodology for creating the benefit-per-ton estimates used in this analysis can consult EPA's "Technical Support Document: Estimating the Benefit per Ton of Reducing $PM_{2.5}$ Precursors from 17 Sectors."[S] Readers can also refer to Fann et al. (2012) for a detailed description of the benefit-per-ton methodology. As described in the documentation, EPA uses a method that is consistent with the cost-benefit analysis that accompanied the 2012 PM NAAQS revision. The benefit-per-ton estimates utilize the concentration-response functions as reported in the epidemiology literature.[T,88] To calculate the total monetized impacts associated with quantified health impacts, EPA applies values derived from a number of sources. For premature mortality, EPA applies a value of a statistical life (VSL) derived from the mortality valuation literature. For certain health impacts, such as

[S] For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed September 9, 2014).
[T] Although we summarize the main issues in this chapter, we encourage interested readers to see the benefits chapter of the RIA that accompanied the PM NAAQS for a more detailed description of recent changes to the quantification and monetization of PM benefits. Note that the cost-benefit analysis was prepared solely for purposes of fulfilling analysis requirements under Executive Order 12866 and was not considered, or otherwise played any part, in the decision to revise the PM NAAQS.

respiratory-related ailments, EPA applies willingness-to-pay estimates derived from the valuation literature. For the remaining health impacts, EPA applies values derived from current cost-of-illness and/or wage estimates.

The documentation cited above also describes that national per-ton estimates were developed for selected PM-related pollutant/source category combinations. The per-ton values calculated therefore apply only to tons reduced from those specific PM-related pollutant/source combinations (e.g., NO_2 emitted from on-road mobile sources; direct PM emitted from electricity generating units). EPA's estimate of $PM_{2.5}$ benefits is therefore based on the total direct $PM_{2.5}$ and PM-related precursor emissions controlled by sector and multiplied by each per-ton value.

As Table 3.12 indicates, EPA projects that the per-ton values for reducing emissions of non-GHG pollutants from both vehicle use and upstream sources such as fuel refineries will increase over time.[U] These projected increases reflect rising income levels, which increase affected individuals' willingness to pay for reduced exposure to health threats from air pollution.[V] They also reflect future population growth and increased life expectancy, which expands the size of the population exposed to air pollution in both urban and rural areas, especially among older age groups with the highest mortality risk.[W]

The benefit-per-ton estimates are subject to a number of assumptions and uncertainties:

The benefit-per-ton estimates used in this analysis reflect specific geographic patterns of emissions reductions and specific air quality and benefits modeling assumptions associated with the derivation of those estimates (see the separate technical documentation that describes the calculation of the national benefit-per-ton estimates).[89,X] Consequently, these estimates may not reflect local variability in population density, meteorology, exposure, baseline health incidence rates, or other local factors associated with the current analysis.

This analysis assumes that all fine particles, regardless of their chemical composition, are equally potent in causing premature mortality. This is an important assumption, because $PM_{2.5}$ produced via transported precursors emitted from stationary sources may differ significantly from direct $PM_{2.5}$ released from diesel engines and other industrial sources. The PM Integrated Science Assessment (ISA), which was twice reviewed by the Science Advisory Board's Clean Air Science Advisory Committee (SAB-CASAC), concluded that "many constituents of $PM_{2.5}$ can be linked with multiple health effects, and the evidence is not yet sufficient to allow

---

[U] As we present in the Proposed Determination document, Appendix C, the standards would yield emission reductions from upstream refining and fuel distribution due to decreased petroleum consumption.

[V] The issue is discussed in more detail in the 2012 PM NAAQS RIA, Section 5.6.8. See U.S. Environmental Protection Agency. (2012). Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter, Health and Environmental Impacts Division, Office of Air Quality Planning and Standards, EPA-452-R-12-005, December 2012. Available on the internet: http://www.epa.gov/ttnecas1/regdata/RIAs/finalria.pdf.

[W] For more information about EPA's population projections, please refer to the following: http://www.epa.gov/air/benmap/models/BenMAPManualAppendicesAugust2010.pdf (See Appendix K)

[X] See also: http://www.epa.gov/airquality/benmap/sabpt.html. The current values available on the webpage have been updated since the publication of the Fann et al., 2012 paper. For more information regarding the updated values, see: http://www.epa.gov/airquality/benmap/models/Source_Apportionment_BPT_TSD_1_31_13.pdf (accessed September 9, 2014).

differentiation of those constituents or sources that are more closely related to specific outcomes."[90] PM composition and the size distribution of those particles vary within and between areas due to source characteristics. Any specific location could have higher or lower contributions of certain PM species and other pollutants than the national average, meaning potential regional differences in health impact of given control strategies. Depending on the toxicity of each PM species reduced by the proposed standards, assuming equal toxicity could over or underestimate benefits.

When estimating the benefit-per-ton values, EPA assumes that the underlying health impact functions for fine particles are linear within the range of ambient concentrations under consideration. Thus, the estimates include health benefits from reducing fine particles in areas with varied concentrations of $PM_{2.5}$, including regions that are in attainment with the fine particle standard. The direction of bias that assuming a linear-no threshold model (or an alternative model) introduces depends upon the "true" functional from of the relationship and the specific assumptions and data in a particular analysis. For example, if the true function identifies a threshold below which health effects do not occur, benefits may be overestimated if a substantial portion of those benefits were estimated to occur below that threshold. Alternately, if a substantial portion of the benefits occurred above that threshold, the benefits may be underestimated because an assumed linear no-threshold function may not reflect the steeper slope above that threshold to account for all health effects occurring above that threshold.

There are several health benefit categories that EPA was unable to quantify due to limitations associated with using benefits-per-ton estimates, several of which could be substantial. Because the NO_X and VOC emission reductions associated with the standards are also precursors to ozone, reductions in NO_X and VOC would also reduce ozone formation and the health effects associated with ozone exposure. Unfortunately, ozone-related benefits-per-ton estimates do not exist due to issues associated with the complexity of the atmospheric air chemistry and nonlinearities associated with ozone formation. The PM-related benefits-per-ton estimates also do not include any human welfare or ecological benefits.

There are many uncertainties associated with the health impact functions that underlie the benefits-per-ton estimates. These include: within-study variability (the precision with which a given study estimates the relationship between air quality changes and health effects); across-study variation (different published studies of the same pollutant/health effect relationship typically do not report identical findings and in some instances the differences are substantial); the application of concentration-response functions nationwide (does not account for any relationship between region and health effect, to the extent that such a relationship exists); extrapolation of impact functions across population (we assumed that certain health impact functions applied to age ranges broader than that considered in the original epidemiological study); and various uncertainties in the concentration-response function, including causality and thresholds. These uncertainties may under- or over-estimate benefits.

EPA has investigated methods to characterize uncertainty in the relationship between $PM_{2.5}$ exposure and premature mortality. EPA's final $PM_{2.5}$ NAAQS analysis provides a more complete picture about the overall uncertainty in $PM_{2.5}$ benefits estimates. For more information, please consult the $PM_{2.5}$ NAAQS Regulatory Impacts Analysis.[91]

The benefit-per-ton unit values used in this analysis incorporate projections of key variables, including atmospheric conditions, source level emissions, population, health baselines, incomes, and technology. These projections introduce additional uncertainties to the benefit per ton estimates.

3.7 Social Cost of Greenhouse Gas Emissions

We estimate the global social benefits of CO_2 emission reductions expected from the 2022-2025 final standards using the SC-CO_2 estimates presented in the *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866* (May 2013, Revised August 2016) ("current TSD").[92] We refer to these estimates, which were developed by the U.S. government, as "SC-CO_2 estimates." The SC-CO_2 is a metric that estimates the monetary value of impacts associated with marginal changes in CO_2 emissions in a given year. It includes a wide range of anticipated climate impacts, such as net changes in agricultural productivity and human health, property damage from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. It is typically used to assess the avoided damages as a result of regulatory actions (i.e., benefits of rulemakings that lead to an incremental reduction in cumulative global CO_2 emissions).

The SC-CO_2 estimates used in the final 2017-2025 RIA and in this analysis were developed over many years, using the best science available, and with input from the public. Specifically, an interagency working group (IWG) that included the EPA and other executive branch agencies and offices used three integrated assessment models (IAMs) to develop the SC-CO_2 estimates and recommended four global values for use in regulatory analyses. The SC-CO_2 estimates were first released in February 2010 and were used to estimate the value of CO_2 benefits in the final 2017-2025 rulemaking.

These SC-CO_2 estimates were developed using an ensemble of the three most widely cited integrated assessment models in the economics literature with the ability to estimate the SC-CO_2. A key objective of the IWG was to draw from the insights of the three models while respecting the different approaches to linking GHG emissions and monetized damages taken by modelers in the published literature. After conducting an extensive literature review, the interagency group selected three sets of input parameters (climate sensitivity, socioeconomic and emissions trajectories, and discount rates) to use consistently in each model. All other model features were left unchanged, relying on the model developers' best estimates and judgments, as informed by the literature. Specifically, a common probability distribution for the equilibrium climate sensitivity parameter, which informs the strength of climate's response to atmospheric GHG concentrations, was used across all three models. In addition, a common range of scenarios for the socioeconomic parameters and emissions forecasts were used in all three models. Finally, the marginal damage estimates from the three models were estimated using a consistent range of discount rates, 2.5, 3.0, and 5.0 percent. See *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866* (February 2010) ("2010 TSD") for a complete discussion of the methods used to develop the estimates and the key uncertainties, and the current TSD for the latest estimates.[93]

In 2013, and after the final LD 2017-2025 rulemaking, the IWG updated the SC-CO_2 estimates using new versions of each IAM. The 2013 update did not revisit the 2010 modeling decisions with regards to the discount rate, reference case socioeconomic and emission scenarios, and equilibrium climate sensitivity distribution. Rather, improvements in the way damages are modeled are confined to those that have been incorporated into the latest versions of the models by the developers themselves and published in the peer-reviewed literature. The model updates that are relevant to the SC-CO_2 estimates include: an explicit representation of sea level rise damages in the Dynamic Integrated Climate and Economy (DICE) and Policy Analysis of the Greenhouse Effect (PAGE) models; updated adaptation assumptions, revisions to ensure damages are constrained by GDP, updated regional scaling of damages, and a revised treatment of potentially abrupt shifts in climate damages in the PAGE model; an updated carbon cycle in the DICE model; and updated damage functions for sea level rise impacts, the agricultural sector, and reduced space heating requirements, as well as changes to the transient response of temperature to the buildup of GHG concentrations and the inclusion of indirect effects of methane emissions in the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) model. The current TSD presents and discusses the 2013 update (including recent minor technical corrections to the estimates).[Y]

The updated estimates continue to represent global measures because of the distinctive nature of the climate change, which is highly unusual in at least three respects. First, emissions of most GHGs contribute to damages around the world independent of the country in which they are emitted. The SC-CO_2 must therefore incorporate the full (global) damages caused by GHG emissions to address the global nature of the problem. Second, the U.S. operates in a global and highly interconnected economy, such that impacts on the other side of the world can affect our economy. This means that the true costs of climate change to the U.S. are larger than the direct impacts that simply occur within the U.S. Third, climate change represents a classic public goods problem because each country's reductions benefit everyone else and no country can be excluded from enjoying the benefits of other countries' reductions, even if it provides no reductions itself. In this situation, the only way to achieve an economically efficient level of emissions reductions is for countries to cooperate in providing mutually beneficial reductions beyond the level that would be justified only by their own domestic benefits. In reference to the public good nature of mitigation and its role in foreign relations, thirteen prominent academics noted that these "are compelling reasons to focus on a global SCC" in a recent article on the SCC (Pizer et al., 2014). In addition, as noted in OMB's Response to Comments on the SC-CO_2, a document discussed further below, there is no bright line between domestic and global damages. Adverse impacts on other countries can have spillover effects on the United States, particularly in the areas of national security, international trade, public health and humanitarian concerns.[94]

The 2010 TSD noted a number of limitations to the SC-CO_2 analysis, including the incomplete way in which the integrated assessment models capture catastrophic and non-catastrophic impacts, their incomplete treatment of adaptation and technological change, uncertainty in the extrapolation of damages to high temperatures, and assumptions regarding risk aversion. Currently integrated assessment models do not assign value to all of the important physical, ecological, and economic impacts of climate change recognized in the climate change literature due to a lack of precise information on the nature of damages and because the science

[Y] Both the 2010 TSD and the current TSD are available at: https://www.whitehouse.gov/omb/oira/social-cost-of-carbon.

incorporated into these models understandably lags behind the most recent research.[Z] The limited amount of research linking climate impacts to economic damages makes the modeling exercise even more difficult. These individual limitations do not all work in the same direction in terms of their influence on the SC-CO_2 estimates, though taken together they suggest that the SC-CO_2 estimates are likely conservative. In particular, the IPCC Fourth Assessment Report (2007), which was the most current IPCC assessment available at the time of the IWG's 2009-2010 review, concluded that "It is very likely that [SC-CO_2 estimates] underestimate the damage costs because they cannot include many non-quantifiable impacts." Since then, the peer-reviewed literature has continued to support this conclusion. For example, the IPCC Fifth Assessment report observed that SC-CO_2 estimates continue to omit various impacts that would likely increase damages.

The EPA and other agencies have continued to consider feedback on the SC-CO_2 estimates from stakeholders through a range of channels, most recently including public comments on the Clean Power Plan rulemaking[95] and others that use the SC-CO_2 in supporting analyses and through regular interactions with stakeholders and research analysts implementing the SC-CO_2 methodology used by the interagency working group. Several comments received on the Draft TAR stated that the SC-CO_2 underestimates climate-related benefits and discussed some of the technical details of the modeling conducted to develop the SC-CO_2 estimates. EPA recognizes the importance of the estimates to be as complete as possible and will continue to follow and evaluate the latest science on impact categories that are omitted or not fully addressed in the IAMs. Some commenters also provided constructive recommendations for potential opportunities to improve the SC-CO_2 estimates in future updates. In addition, OMB sought public comment on the approach used to develop the SC-CO_2 estimates through a separate comment period and published a response to those comments in 2015.[AA]

After careful evaluation of the full range of comments submitted to OMB, the IWG continues to recommend the use of the SC-CO_2 estimates in regulatory impact analysis while also continuing to engage in research on modeling and valuation of climate impacts. Currently, the IWG is seeking advice from the National Academies of Sciences, Engineering and Medicine on how to approach future updates to ensure that the estimates continue to reflect the best available scientific and economic information on climate change.[BB] An Academies committee, "Assessing Approaches to Updating the Social Cost of Carbon," (Committee) will provide expert, independent advice on the merits of different technical approaches for modeling and highlight research priorities going forward. EPA will evaluate its approach based upon any feedback received from the Academies' panel.

[Z] Climate change impacts and SCC modeling is an area of active research. For example, see: (1) Howard, Peter, "Omitted Damages: What's Missing from the Social Cost of Carbon." March 13, 2014, http://costofcarbon.org/files/Omitted_Damages_Whats_Missing_From_the_Social_Cost_of_Carbon.pdf; and (2) Electric Power Research Institute, "Understanding the Social Cost of carbon: A Technical Assessment," October 2014, www.epri.com.

[AA] See https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf.

[BB] The Academies' review will be informed by public comments and focus on the technical merits and challenges of potential approaches to improving the SC-CO2 estimates in future updates. See https://www.whitehouse.gov/blog/2015/07/02/estimating-benefits-carbon-dioxide-emissions-reductions.

To date, the Committee has released an interim report, which recommended against doing a near term update of the SC-CO_2 estimates. For future revisions, the Committee recommended the IWG move efforts towards a broader update of the climate system module consistent with the most recent, best available science, and also offered recommendations for how to enhance the discussion and presentation of uncertainty in the SC-CO_2 estimates. Specifically, the Committee recommended that "the IWG provide guidance in their technical support documents about how [SC-CO_2] uncertainty should be represented and discussed in individual regulatory impact analyses that use the [SC-CO_2]" and that the technical support document for each update of the estimates present a section discussing the uncertainty in the overall approach, in the models used, and uncertainty that may not be included in the estimates.[CC] In August 2016, the IWG issued revisions to the SC-CO_2 Technical Support Document that responded to interim recommendations from the Academies regarding the presentation and discussion of uncertainty. The revision did not modify methodological decisions or change the SC-CO_2 estimates themselves. The Committee will release a final report in early 2017 with longer-term recommendations for updating the estimates.

The current SC-CO_2 estimates are as follows: \$15, \$49, \$72, and \$150 per ton of CO_2 emissions in the year 2022 (2015\$).[DD] The first three values are based on the average SC-CO_2 from the three IAMs, at discount rates of 5, 3, and 2.5 percent, respectively. SC-CO_2 estimates for several discount rates are included because the literature shows that the SC-CO_2 is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context (where costs and benefits are incurred by different generations). The fourth value is the 95th percentile of the SC-CO_2 from all three models at a 3 percent discount rate. It is included to represent lower probability but higher - impact outcomes from climate change, which are captured further out in the tail of the SC-CO_2 distribution, and while less likely than those reflected by the average SC-CO_2 estimates, would be much more harmful to society and therefore, are relevant to policy makers.

The current estimates, which are the same as those used in the Draft TAR, are higher than those used to analyze the CO_2 impacts in the final LD 2017-2025 rulemaking, which preceded the 2013 SC-CO_2 update and were published in the 2010 SC-CO_2 TSD. By way of comparison, the four SC-CO_2 estimates used to analyze the CO_2 impacts for the final LD 2017-2015 rulemaking were \$8.3, \$31, \$49, and \$96 per metric ton in 2022 (2015\$).[EE] As previously noted,

---

[CC] National Academies of Sciences, Engineering, and Medicine. (2016). Assessment of Approaches to Updating the Social Cost of Carbon: Phase 1 Report on a Near-Term Update. Committee on Assessing Approaches to Updating the Social Cost of Carbon, Board on Environmental Change and Society. Washington, DC: The National Academies Press. doi: 10.17226/21898. See Executive Summary, page 1, for quoted text.

[DD] The current version of the TSD is available at: https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf. All of the SC-CO_2 TSDs present SC-CO2 in 2007\$ per metric ton. The unrounded estimates from the current TSD were adjusted to 2015\$ using GDP Implicit Price Deflator (1.130), http://www.bea.gov/iTable/index_nipa. The estimates presented in this document were rounded to two significant digits.

[EE] The SC-CO2 TSDs present SC-CO2 in 2007\$; see https://www.whitehouse.gov/omb/oira/social-cost-of-carbon for both TSDs. The estimates used in the final 2017-2025 rulemaking were adjusted to 2010\$ using GDP Implicit Price Deflator. The estimates presented in the Draft TAR were in 2013\$. The estimates presented in the Proposed Determination have not changed since the Draft TAR but were adjusted to 2015\$ for consistency with the rest of the IWG updated these estimates in 2013 using new versions of each integrated assessment model but did not revisit the modeling decisions. Table 3.14 presents the current global SC-CO_2 estimates for select years between 2022 and 2050. In order to calculate the dollar value for emission reductions, the SC-CO_2 estimate for each emissions year would be applied to changes in CO_2 emissions for that year, and then discounted back to the analysis year using the same discount rate used to estimate the SC-CO_2. The SC-CO_2 increases over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater climate change. Note that the interagency group estimated the growth rate of the SC-CO_2 directly using the three integrated assessment models rather than assuming a constant annual growth rate. This helps to ensure that the estimates are internally consistent with other modeling assumptions. Appendix Section C of the Proposed Determination document reports the updated GHG benefits in select model years and calendar years.

Table 3.14 Social Cost of CO_2, 2022-2050 (in 2015$ per metric ton)*

	Discount Rate and Statistic			
Year	5% Average	3% Average	2.5% Average	High Impact (3% at 95th percentile)
2022	$15	$49	$72	$150
2023	$15	$50	$73	$150
2024	$15	$51	$75	$150
2025	$16	$52	$77	$160
2030	$18	$57	$82	$170
2040	$24	$68	$95	$210
2050	$29	$78	$110	$240

Note:
* These SC-CO_2 values are stated in $/metric ton and rounded to two significant figures. The estimates vary depending on the year of CO_2 emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator.

One limitation of the primary benefits analysis in the 2017-2025 final rulemaking is that it did not include the valuation of non-CO_2 GHG impacts (CH_4, N_2O, HFC-134a). Specifically, the IWG did not estimate the social costs of non-CO_2 GHG emissions using an approach analogous to the one used to estimate the SC-CO_2. While there were other estimates of the social cost of non-CO_2 GHGs in the peer review literature, the methodologies underlying those estimates were inconsistent with the methodology the IWG used to estimate the SC-CO_2. As discussed in the 2017-2025 final rulemaking, there is considerable variation among these published estimates in the models and input assumptions they employ.[FF] These studies differ in the emission perturbation year, employ a wide range of constant and variable discount rate specifications, and consider a range of baseline socioeconomic and emissions scenarios that have been developed

the Proposed Determination. The unrounded estimates from the current TSD were adjusted to 2015$ using GDP Implicit Price Deflator (1.130), http://www.bea.gov/iTable/index_nipa. The estimates presented in this document were rounded to two significant digits.

[FF] The researchers cited in the 2017-2015 RIA include: Fankhauser (1994); Kandlikar (1995); Hammitt et al. (1996); Tol et al. (2003); Tol (2004); and Hope and Newberry (2006).

over the last 20 years. EPA also determined that the estimates in the literature were most likely underestimates due to changes in the underlying science since their publication.[GG]

However, EPA recognized that non-CO_2 GHG impacts associated with these standards (e.g., net reductions in CH_4, N_2O, and HFC-134a) would provide benefits to society. To understand the potential implication of omitting these benefits, EPA conducted sensitivity analysis using an approximation approach based on global warming potential (GWP) gas comparison metrics that has been used in previous rulemakings. The EPA also sought public comments on the valuation of non-CO_2 GHG impacts in the proposed LD 2017-2025 rulemaking and other previous rulemakings (e.g., U.S. EPA 2012).[96] In general, the commenters strongly encouraged the EPA to incorporate the monetized value of non-CO_2 GHG impacts into the benefit cost analysis, however they noted the challenges associated with the GWP-approach, as discussed further below, and encouraged the use of directly-modeled estimates of the SC-CH_4 to overcome those challenges.

In August 2016, the IWG issued an Addendum to the current TSD that presents estimates of the SC-CH_4 and SC-N_2O for use in regulatory impact analysis ("IWG non-CO_2 Addendum").[97] The IWG's SC-CH_4 and SC-N_2O estimates are taken from a paper by Marten et al. (2014), which provided the first set of published SC-CH_4 and SC-N_2O estimates that are consistent with the modeling assumptions underlying the SC-CO_2.[98] Specifically, the estimation approach of Marten et al. used the same set of three IAMs, five socioeconomic and emissions scenarios, equilibrium climate sensitivity distribution, three constant discount rates, and aggregation approach used by the IWG to develop the SC-CO_2 estimates. The aggregation method involved distilling the 45 distributions of the SC-CH_4 and of the SC-N_2O produced for each emissions year into four estimates: the mean across all models and scenarios using a 2.5 percent, 3 percent, and 5 percent discount rate, and the 95th percentile of the pooled estimates from all models and scenarios using a 3 percent discount rate. Marten et al. also used the same rationale as the IWG to develop global estimates of the SC-CH_4 and SC-N_2O, given that methane and N_2O are global pollutants.

The IWG non-CO_2 Addendum discusses the basis for atmospheric lifetime and radiative efficacy of methane and N_2O used by Marten et. al. Specifically, Marten et al. based atmospheric lifetime and radiative efficacy on the estimates reported by the IPCC in their Fourth Assessment Report (AR4, 2007), including an adjustment in the radiative efficacy of methane to account for its role as a precursor for tropospheric ozone and stratospheric water. These values represent the same ones used by the IPCC in AR4 for calculating GWPs. At the time Marten et al. developed their estimates of the SC-CH_4, AR4 was the latest assessment report by the IPCC. The IPCC updates GWP estimates with each new assessment, and in the most recent assessment, AR5, the latest estimate of the methane GWP ranged from 28-36, compared to a GWP of 25 in AR4. The updated values reflect a number of changes: changes in the lifetime and radiative efficiency estimates for CO_2, changes in the lifetime estimate for methane, and changes in the correction factor applied to methane's GWP to reflect the effect of methane emissions on other climatically important substances such as tropospheric ozone and stratospheric water vapor. In addition, the

[GG] See the 2017-2025 RIA, page 7-7, for complete discussion. Literature included studies primarily from the mid-1990s through early 2000s. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100EZI1.PDF?Dockey=P100EZI1.PDF.

range presented in the latest IPCC report reflects different choices regarding whether to account for how biogenic and fossil methane have different carbon cycle effects, and for whether to account for climate feedbacks on the carbon cycle for both methane and CO_2 (rather than just for CO_2 as was done in AR4).[99,HH]

The IWG non-CO_2 Addendum discusses the SC-CH_4 and SC-N_2O estimates, (presented below in Table 3.15), and compare them with other recent estimates in the literature. A direct comparison of the estimates with all of the other published estimates is difficult, given the differences in the models and socioeconomic and emissions scenarios, but results from three relatively recent studies offer a better basis for comparison (see Hope (2006), Marten and Newbold (2012), Waldhoff et al. (2014)). Marten et al. found that, in general, the SC-CH_4 estimates from their 2014 paper are higher than previous estimates and the SC-N_2O estimates from their 2014 paper fall within the range from Waldhoff et al. The higher SC-CH_4 estimates are partially driven by the higher effective radiative forcing due to the inclusion of indirect effects from methane emissions in their modeling. Marten et al., similar to other recent studies, also find that their directly modeled SC-CH_4 and SC-N_2O estimates are higher than the GWP-weighted estimates. More detailed discussion of the SC-CH_4 and SC-N_2O estimation methodology, results and a comparison to other published estimates can be found in Marten et al. (2014).

The resulting SC-CH_4 and SC-N_2O estimates are presented in Table 3.15. The tables do not include HFC-134a because EPA is unaware of analogous estimates.

Table 3.15 Social Cost of CH4 and Social Cost of N2O, 2012-2050 (in 2015$ per metric ton)

	Social Cost of CH4				Social Cost of N2O			
Year	5% (Avg)	3% (Avg)	2.5% (Avg)	High Impact (3% at 95th percentile)	5% (Avg)	3% (Avg)	2.5% (Avg)	High Impact (3% at 95th percentile)
2022	$660	$1,400	$1,900	$3,800	$5,700	$18,000	$26,000	$46,000
2023	$680	$1,500	$1,900	$4,000	$5,900	$18,000	$26,000	$47,000
2024	$710	$1,500	$2,000	$4,100	$6,000	$19,000	$27,000	$49,000
2025	$730	$1,600	$2,000	$4,200	$6,200	$19,000	$27,000	$50,000
2030	$860	$1,800	$2,300	$4,700	$7,100	$21,000	$31,000	$55,000
2040	$1,100	$2,300	$2,900	$6,200	$9,500	$26,000	$36,000	$68,000
2050	$1,500	$2,800	$3,500	$7,600	$12,000	$31,000	$42,000	$81,000

Note:
* These SC-CH_4 and SC-N_2O values are stated in $/metric ton and rounded to two significant figures. The estimates vary depending on the year of emissions and are defined in real terms, i.e., adjusted for inflation using the GDP implicit price deflator. In addition, the estimates in this table have been adjusted to reflect the minor technical

[HH] Consistent with the Draft TAR, the Proposed Determination uses 100-year GWP values for CO_2 equivalency calculations that are consistent with the GHG emissions inventories and the IPCC Fourth Assessment Report (AR4), i.e., 25 for methane. The IPCC reported the same 100-year GWP for N_2O (298) in AR4 and AR5.

corrections to the SC-CO_2 estimates described above. See Corrigendum to Marten et al. (2014) for more details http://www.tandfonline.com/doi/abs/10.1080/14693062.2015.1070550 .

This Proposed Determination analysis updates the non-CO_2 GHG benefits presented in the 2017-2025 final rule by using the IWG's estimates of SC-CH_4 and SC-N_2O.[II] As discussed in the IWG non-CO_2 Addendum, the application of directly modeled estimates from Marten et al. (2014) to benefit-cost analysis of a regulatory action is analogous to the use of the SC-CO_2 estimates. Specifically, the SC-CH_4 and SC-N_2O estimates in Table 3.15 are used to monetize the benefits of reductions in methane and N_2O emissions, respectively, expected as a result of the 2022-2025 standards. Forecast changes in methane (or N_2O) emissions in a given year, expected as a result of the standards, are multiplied by the SC-CH_4 (or SC-N_2O) estimate for that year. To obtain a present value estimate, the monetized stream of future non-CO_2 GHG benefits are discounted back to the analysis year using the same discount rate used to estimate the social cost of the non-CO_2 GHG emission changes. In addition, the limitations for the SC-CO_2 estimates discussed above likewise apply to the SC-CH_4 and SC-N_2O estimates, given the consistency in the methodology. See the IWG non-CO_2 Addendum for additional details about the peer review conducted of the application of the Marten et al. (2014) non-CO_2 social cost estimates in regulatory analysis.

The summary of GHG (CO_2, methane, N_2O) benefits are presented for select model years and calendar years is in Appendix Section C of the Proposed Determination document.

EPA is unaware of estimates of the social cost of HFC-134a that are analogous to the SC-CO_2, SC-CH_4, and SC-N_2O estimates discussed above. In the 2017-2025 final rulemaking, EPA used the GWP for HFC-134a to convert the emissions of this gas to CO_2 equivalents, which were then valued using the SC-CO_2 estimates. These estimates were presented in a sensitivity analysis due to the limitations associated with using the GWP approach to value changes in non-CO_2 GHG emissions.

The GWP measures the cumulative radiative forcing from a perturbation of a non-CO_2 GHG relative to a perturbation of CO_2 over a fixed time horizon, often 100 years. The GWP mainly reflects differences in the radiative efficiency of gases and differences in their atmospheric lifetimes. While the GWP is a simple, transparent, and well-established metric for assessing the relative impacts of non-CO_2 emissions compared to CO_2 on a purely physical basis, there are several well-documented limitations in using it to value non-CO_2 GHG benefits, as discussed in the 2010 SC-CO_2 TSD and previous rulemakings.[100] In particular, several recent studies found that GWP-weighted benefit estimates for methane are likely to be lower than the estimates derived using directly modeled social cost estimates for these gases. Gas comparison metrics, such as the GWP, are designed to measure the impact of non-CO_2 GHG emissions relative to CO_2 at a specific point along the pathway from emissions to monetized damages (depicted in Figure 3.4), and this point may differ across measures.

[II] The IWG SC-CH4 and SC-N2O estimates presented in this TSD are the same as the SC-CH4 and SC-N2O estimates presented in the Draft TAR except they have been adjusted to 2015$ instead of 2013$. The estimates published in the Draft TAR were labeled as "Marten et al. (2014)" estimates.

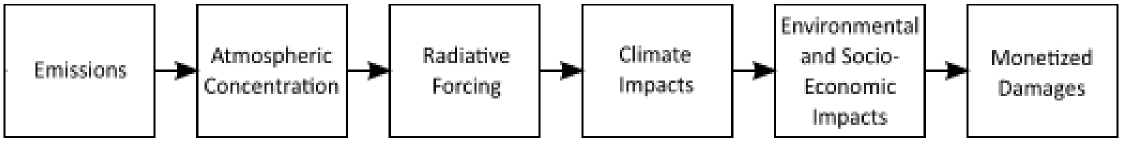


Figure 3.4 Path from GHG Emissions to Monetized Damages (Source: Marten et al., 2014)

The GWP is not ideally suited for use in benefit-cost analyses to approximate the social cost of non-CO_2 GHGs because it ignores important nonlinear relationships beyond radiative forcing in the chain between emissions and damages. These can become relevant because gases have different lifetimes and the SC-CO_2 takes into account the fact that marginal damages from an increase in temperature are a function of existing temperature levels. Another limitation of gas comparison metrics for this purpose is that some environmental and socioeconomic impacts are not linked to all of the gases under consideration, or radiative forcing for that matter, and will therefore be incorrectly allocated. For example, the economic impacts associated with increased agricultural productivity due to higher atmospheric CO_2 concentrations included in the SC-CO_2 would be incorrectly allocated to methane emissions with the GWP-based valuation approach.

Also of concern is the fact that the assumptions made in estimating the GWP are not consistent with the assumptions underlying SC-CO_2 estimates in general, and the SC-CO_2 estimates developed by the IWG more specifically. For example, the 100-year time horizon usually used in estimating the GWP is less than the approximately 300-year horizon the IWG used in developing the SC-CO_2 estimates. The GWP approach also treats all impacts within the time horizon equally, independent of the time at which they occur. This is inconsistent with the role of discounting in economic analysis, which accounts for a basic preference for earlier over later gains in utility and expectations regarding future levels of economic growth.

The changes in HFC-134a emissions occur through model year 2021, at which point use of HFC-134a in new vehicles is prohibited under the Significant New Alternatives Policy (SNAP). As discussed in Chapter 5.2.9.2, EPA expects that HFC-134a will be entirely replaced by refrigerants with lower GWPs by model year 2021. In other words, there will be no further reductions in HFC-134a emissions after model year 2021. Given that this Proposed Determination considers years after 2021, there are no changes in impacts to report for HFC-134a. See Chapter 2.2.9.2 of this TSD for complete discussion, including EPA's assessment about the transition to use of low-GWP alternative refrigerants.

3.8 Benefits from Reduced Refueling Time

The total time spent pumping and paying for fuel, and driving to and from fueling stations, represents an economic cost to drivers and other vehicle occupants. Increased driving range provides a benefit to individuals arising from the value of the time saved when refueling events are eliminated. As described in this section, the EPA calculates this benefit by applying DOT-recommended values of travel time savings to estimates of how much time is saved.

The increases in fuel economy resulting from the standards are expected to lead to some increase in vehicle driving range. The extent of this increase depends on manufacturers' decisions to apply reduced fuel consumption requirements towards increasing range, rather than reducing tank size while maintaining range. For the 2012 FRM, EPA conducted a regression analysis to identify the relationship between fuel economy and fuel tank size for different vehicle classes based on historical data. Trends in fuel tank size for a number of redesigned vehicles were also investigated. Based on these analyses, fuel economy improvements were assumed to be entirely realized as improvements in driving range, due to insufficient evidence to indicate that fuel tank size is reduced as vehicle fuel economy is improved. EPA is using the assumption from Chapter 10.8 of the Draft TAR that fuel tank sizes remain constant. EPA did not receive comments on this topic, and we have not seen evidence to suggest that reductions in vehicle tank size are occurring. Thus we believe that using the Draft TAR values is still appropriate; however, we will continue to monitor trends in fuel tank designs and vehicle range.

No direct estimates of the value of extended vehicle range or reduced fuel tank size are readily available. Instead, the EPA analysis calculates the reduction in the annual amount of time a driver would spend filling its fuel tank; this reduced time could result either from fewer refueling events, if new fuel tanks stay the same size, or from less time spent filling the tank during each refueling stop, if new fuel tanks are made proportionately smaller. As discussed in Section 3.4 above, the average number of miles each type of vehicle is driven annually would likely increase under the regulation, as drivers respond to lower fuel expenditures (the "rebound effect"). The estimates of refueling time in effect allow for this increase in vehicle use. However, the estimate of the rebound effect does not account for any reduction in net operating costs from lower refueling time. Because the rebound effect should measure the change in VMT with respect to the net change in overall operating costs, refueling time costs would ideally factor into this calculation. The effect of this omission is expected to be minor because refueling time savings are generally small relative to the value of reduced fuel expenditures.

The savings in refueling time are calculated as the total amount of time the driver of a typical vehicle would save each year as a consequence of pumping less fuel into the vehicle's tank. The calculation also includes a fixed time per refill event of 3.5 minutes which would not occur as frequently due to the fewer number of refills.

The calculation uses the reduced number of gallons consumed and divides that value by the tank volume and refill amount to get the number of refills, then multiplies that by the time per refill to determine the number of hours saved in a given year. The calculation then applies DOT-recommended values of travel time savings to convert the resulting time savings to their economic value. For this analysis, EPA uses the input metrics shown in Table 3.16. The refueling benefits are presented in Appendix C.3 to the Proposed Determination document.

Table 3.16 Metrics Used in Calculating the Value of Refueling Time

Metric	Value
Average tank refill percentage	65%
Average tank volume	15 gallons
Fuel dispense rate	10 gal/min
Fixed time per refill	3.5 minutes
Wage rate for the value of refill time	$25.72 in 2015$
Number of people in vehicle	1.2
Wage growth rate, 2014 base year	1.1%

The equation used by EPA to calculate refueling benefits is shown below. This is the same approach and equation as was used in the Draft TAR.

$$Refueling\ Benefit = \left(\frac{Gal_{reference} - Gal_{policy}}{Gal\ per\ refill}\right) \times \left(\frac{Gal\ per\ refill}{Fuel\ dispense\ rate} + time\ per\ refill\right) \times \left(\frac{\$}{hr}\right)_{labor}$$

3.9 Benefits and Costs from Additional Driving

3.9.1 Travel Benefit

The increase in travel associated with the rebound effect produces additional benefits to vehicle drivers, which reflect the value of the added (or more desirable) social and economic opportunities that become accessible with additional travel. The analysis estimates the economic benefits from increased rebound-effect driving as the sum of fuel expenditures incurred plus the vehicle owner/operator surplus from the additional accessibility it provides. As evidenced by the fact that vehicles make more frequent or longer trips when the cost of driving declines, the benefits from this added travel exceed added expenditures for the fuel consumed. Note that the amount by which the benefits from this increased driving exceed its increased fuel costs measures the net benefits from the additional travel, usually referred to as increased consumer surplus or, in this case, increased driver surplus.

The equation for the calculation of the total travel benefit is shown below. This is the same approach and equation as was used in the Draft TAR.

$$Travel\ Benefit = (VMT_{rebound})\left(\frac{\$}{mi}\right)_{policy} + \left(\frac{1}{2}\right)(VMT_{rebound})\left[\left(\frac{\$}{mile}\right)_{reference} - \left(\frac{\$}{mile}\right)_{policy}\right]$$

The analysis estimates the economic value of the increased owner/operator surplus provided by added driving using the conventional approximation, which is one half of the product of the decline in vehicle operating costs per vehicle-mile and the resulting increase in the annual number of miles driven. Because it depends on the extent of improvement in fuel economy, the value of benefits from increased vehicle use changes by model year and varies among alternative standards. Under even those alternatives that would impose the highest standards, however, the magnitude of the surplus from additional vehicle use represents a small fraction of this benefit. The travel benefits are presented in Appendix C.3 to the Proposed Determination document.

3.9.2 Costs Associated with Crashes, Congestion and Noise

In contrast to the benefits of additional driving are the costs associated with that driving. If net operating costs of the vehicle decline, then we expect a positive rebound effect. Increased vehicle use associated with a positive rebound effect also contributes to increased traffic congestion, motor vehicle crashes, and highway noise. Depending on how the additional travel is distributed throughout the day and on where it takes place, additional vehicle use can contribute to traffic congestion and delays by increasing traffic volumes on facilities that are already heavily traveled during peak periods. These added delays impose higher costs on drivers and other vehicle occupants in the form of increased travel time and operating expenses. Because drivers do not take these added costs into account in deciding when and where to travel, they must be accounted for separately as a cost of the added driving associated with the rebound effect.

EPA relies on estimates of congestion, crash, and noise costs caused light-duty vehicles developed by the Federal Highway Administration to estimate the increased external costs caused by added driving due to the rebound effect. The FHWA estimates are intended to measure the increases in costs from added congestion, property damages and injuries in traffic crashes, and noise levels caused by various classes of vehicles that are borne by persons other than their drivers (or “marginal” external costs). EPA employed estimates from this source previously in the analysis accompanying the light-duty 2012-2016 vehicle rulemaking. We continue to find them appropriate for this analysis after reviewing the procedures used by FHWA to develop them and considering other available estimates of these values.

FHWA’s congestion cost estimates focus on freeways because non-freeway effects are less serious due to lower traffic volumes and opportunities to re-route around the congestion. The agencies, however, applied the congestion cost to the overall VMT increase, though the fraction of VMT on each road type used in MOVES range from X to Y percent of the vehicle miles on freeways for light-duty vehicles. The results of this analysis potentially overestimate the congestions costs associated with increased vehicle use, and thus lead to a conservative estimate of net benefits.

EPA has used FHWA’s “Middle” estimates for marginal congestion, crash, and noise costs caused by increased travel from vehicles. This approach is consistent with the methodology used in both LD and HD GHG rules and in the Draft TAR. These costs are multiplied by the annual increases in vehicle miles travelled from the rebound effect to yield the estimated increases in congestion, crash, and noise externality costs during each future year. The values used are shown in Table 3.17. The costs associated with crashes, congestion and noise are presented in Appendix C.3 to the Proposed Determination document.

Table 3.17 Metrics Used to Calculate the Costs Associated with Congestion, Crashes and Noise Linked to Rebound Miles Traveled (2015$)

Metric	Value
Congestion	$0.0600 per mile
Crashes	$0.0259 per mile
Noise	$0.0008 per mile

3.10 Discounting Future Benefits and Costs

The benefits and costs are analyzed using 3 percent and 7 percent discount rates, consistent with current OMB guidance.[JJ] These rates are intended to represent consumers’ preference for current over future consumption (3 percent), and the real rate of return on private investment (7 percent) which indicates the opportunity cost of capital. However, neither of these rates

[JJ] Office of Management and Budget (2003). “Circular A-4.” https://www.whitehouse.gov/omb/circulars_a004_a-4/. Discounting involving the Social Cost of Carbon (SC-CO_2) values uses several discount rates because the literature shows that the SC-CO_2 is quite sensitive to assumptions about the discount rate, and because no consensus exists on the appropriate rate to use in an intergenerational context (where costs and benefits are incurred by different generations). Refer to Section 10.7 for more information.

necessarily represents the discount rate that individual decision-makers use, nor do they reflect the rates in OMB Circular A-94 Appendix C, which are revised annually.[KK] The 2015 Appendix lists real (i.e., inflation-adjusted) discount rates between 0.3 percent (for a 3-year period) and 1.5 percent (for a 30-year time horizon). All costs and benefits are discounted to 2016 except for those considered in payback analyses where costs and benefits are discounted to the first year of a vehicle's life.

3.11 Additional Costs of Vehicle Ownership

The discussion here regarding sales taxes, insurance and financing costs pertains only to our payback analysis. Here we discuss some of the inputs used for that payback analysis. We present the results of our payback analysis in Appendix C.2.4 to the Proposed Determination document.

3.11.1 Sales Taxes

When consumers consider their total cost of ownership of a vehicle, or its potential payback, they may consider the sales taxes they have to pay at the time of purchasing the vehicle. As these costs are transfer payments, they are not included in the societal costs of the program, but they are included as one of the increased costs to the consumer for these standards when we calculate costs that the consumer pays out for vehicle ownership as part of our payback analysis. In the 2012 FRM, the agencies took the most recent auto sales taxes by state and weighted them by population by state to determine a national weighted-average sales tax of 5.46 percent.[LL] We continue to use that value as we did in the Draft TAR.

3.11.2 Insurance Costs

The agencies considered the standards' impact to consumers' auto insurance expenses over vehicle lifetimes. More expensive vehicles will require more expensive collision and comprehensive (e.g., theft) car insurance. The scope of this analysis is to estimate the increased cost to the consumer for these standards, not the increase in societal costs due to collision and property damage. The increase in insurance costs was estimated from the average value of collision plus comprehensive insurance as a proportion of average new vehicle price. Collision plus comprehensive insurance represent the portion of insurance costs that depend on vehicle value. In the 2012 FRM, we found that dividing the cost to insure a new vehicle by the average price of a new vehicle gives the proportion of comprehensive plus collision insurance as 1.86 percent of the price of a vehicle. As vehicles' values decline with vehicle age, comprehensive and collision insurance premiums likewise decline. We continue to use the same approach in this analysis as was used in the 2012 FRM and again in the Draft TAR.

[KK] Office of Management and Budget (2015). "Circular A-94 Appendix C, Revised November 2015." https://www.whitehouse.gov/omb/circulars_a094/a94_appx-c.

[LL] See http://www.factorywarrantylist.com/car-tax-by-state.html (first accessed April 5, 2012, last accessed on November 15, 2016). Note that county, city, and other municipality-specific taxes were excluded from the weighted averages, as the variation in locality taxes within states, lack of accessible documentation of locality rates, and lack of availability of weights to apply to locality taxes complicate the ability to reliably analyze the subject at this level of detail. Localities with relatively high automobile sales taxes may have relatively fewer auto dealerships, as consumers would endeavor to purchase vehicles in areas with lower locality taxes, therefore reducing the impact of the exclusion of municipality-specific taxes from this analysis.

3.11.3 Financing Costs

When purchasing a new car, most consumers either finance the purchase via a loan or lease the vehicle as opposed to paying for the car in cash. Our payback analysis has considered these financing costs--the interest rates paid on the new car loan--for 3 different loan periods: 4-year, 5-year and the increasingly common 6-year loan. For those loans, we have used interest rates of 4.25 percent.[101] We did not estimate payback periods in the Draft TAR for loan purchased vehicles.

REFERENCES

[1] Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2016," Table 10.1, epa.gov/fuel-economy/trends-report, November 2016.
[2] Ibid.
[3] How Do Motorists' Own Fuel Economy Estimates Compare with Official Government Ratings? A Statistical Analysis," David Greene et al, University of Tennessee, October 1, 2015.
[4] U.S. EPA. MOVES Motor Vehicle Emissions Simulator https://www.epa.gov/moves/moves2014a-latest-version-motor-vehicle-emission-simulator-moves,Version 2014a. November, 2015.
[5] U.S. EPA. Population and Activity of On-road Vehicles in MOVES2014. EPA-420-R-16-003a. March 2016.
[6] Winebrake, J.J., Green, E.H., Comer, B., Corbett, J.J., Froman, S., 2012. "Estimating the direct rebound effect for on-road freight transportation," Energy Policy 48, 252-259.
[7] Greene, D.L., Kahn, J.R., Gibson, R.C., 1999, "Fuel economy rebound effect for U.S. household vehicles," The Energy Journal, 20.
[8] Greening, L.A., Greene, D.L., Difiglio, C., 2000, "Energy efficiency and consumption — the rebound effect — a survey," Energy Policy, 28, 389-401.
[9] Sorrell, S. and Dimitropoulos, J., "UKERC Review of Evidence of the Rebound Effect, Technical Report 2: Econometric Studies," Sussex Energy Group, Working Paper, 2007.
[10] Pickrell, D. and Schimek, P., 1999. "Growth in Motor Vehicle Ownership and Use: Evidence from the Nationwide Personal Transportation Survey," Journal of Transportation and Statistics, vol. 2, no. 1, pp. 1-17. [EPA-HQ-OAR-2010-0799-00027].
[11] Puller, S. and Greening, L., 1999. "Household Adjustment to Gasoline Price Change: An Analysis Using Nine Years of U.S. Survey Data," Energy Economics 21(1):37-52. [EPA-HQ-OAR-2010-0799-0754].
[12] Pickrell, D. and Schimek, P., 1999. "Growth in Motor Vehicle Ownership and Use: Evidence from the Nationwide Personal Transportation Survey," *Journal of Transportation and Statistics*, vol. 2, no. 1, pp. 1-17. [EPA-HQ-OAR-2010-0799-0027].
[13] Small, K. and Van Dender, K., 2007a. "Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect." The Energy Journal, vol. 28, no. 1, pp. 25-51. [EPA-HQ-OAR-2010-0799-0755].
[14] Small, K. and Van Dender, K., 2007b. "Long Run Trends in Transport Demand, Fuel Price Elasticities and Implications of the Oil Outlook for Transport Policy," OECD/ITF Joint Transport Research Centre Discussion Papers 2007/16, OECD, International Transport Forum. [EPA-HQ-OAR-2010-0799-0756].
[15] Hymel, K. M., Small, K. A., and Van Dender, K., "Induced demand and rebound effects in road transport," Transportation Research Part B: Methodological, Volume 44, Issue 10, December 2010, Pages 1220-1241, ISSN 0191-2615, DOI: 10.1016/j.trb.2010.02.007. [EPA-HQ-OAR-2010-2010-0799-0758].
[16] Greene, David, 2012. "Rebound 2007: Analysis of U.S. light-duty vehicle travel statistics," Energy Policy, vol. 41, pp. 14-28. [EPA-HQ-OAR-2010-0799-0759].
[17] Bento, A., Goulder, L., Jacobsen, M. and Haefen, R., 2009, "Distributional and Efficiency Impacts of Increased U.S. Gasoline Taxes, American Economic Review, 99:3 667-699.
[18] Wadud, Z., Graham, D.J., Noland, R.B., 2009. Modelling fuel demand for different socio-economic groups. Applied Energy 86, 2740-2749.
[19] Dargay, J.M. and Gately, D., 1997. "The demand for transportation fuels: imperfect price-reversibility?" Transportation Research Part B 31(1), [EPA-HQ-OAR-2010-0799-076], Sentenac-Chemin, E., 2012, "Is the price effect on fuel consumption symmetric: Some evidence from an empirical study," Energy Policy, Volume 41, pp. 59-65 [EPA-HQ-OAR-2010-0799-0762].
[20] Gately, D., 1993. "The Imperfect Price-Reversibility of World Oil Demand," The Energy Journal, International Association for Energy Economics, vol. 14(4), pp. 163-182. [EPA-HQ-OAR-2010-0799-0763].
[21] Su, Q., 2012, A quantile regression analysis of the rebound effect: Evidence from the 2009 National Household Transportation Survey in the United States, Energy Policy 45, pp. 368–377.
[22] Linn, J., 2013, "The Rebound Effect of Passenger Vehicles," RFF Discussion Paper, No. 13-19 [EPA-HQ-OAR-2010-0799-0761].
[23] Lui, Y.,Tremblay, J. and Cirillo, C., 2014. "An integrated model for discrete and continuous decisions with application to vehicle ownership, type and usage," Transportation Research Part A, pp. 315-328.
[24] Frondel, M., and Vance, C., 2013. Re-Identifying the Rebound: What about Asymmetry? Energy Journal 34 (4):43-54.

[25] Gillingham, K., 2014, Identifying the Elasticity of Driving: Evidence from a Gasoline Price Shock. Regional Science & Urban Economics 47 (4):13-24.
[26] Wang, T. and Chen, C., 2014. "Impact of fuel price on vehicle miles traveled (VMT): do the poor respond in the same way as the rich?" Transportation 41(1): 91-105.
[27] Hymel, K. M. and Small, K. A., 2015, "The rebound effect for automobile travel: Asymmetric response to price changes and novel features of the 2000s," Energy Economics, 49 (2015) 93-103 [EPA-HQ-OAR-2015-0827-0034].
[28] West, J., Hoekstra, M., Meer, J., Puller, S., 2015, "Vehicle Miles (Not) Traveled: Why Fuel Economy Requirements Don't Increase Household Driving" National Bureau of Economic Research (NBER), NBER Working Paper Series, Working Paper 21194, http://www.nber.org/papers/w21194.
[29] De Borger, B. Mulalic, I., and Rouwendal, J.,2016, *Measuring the rebound effect with micro data: A first difference approach*, Journal of Environmental Economics and Management, 79, 1–17.
[30] Gillingham, K., Rapson, D., Wagner, G., 2016, "The Rebound Effect and Energy Efficiency Policy," Review of Environmental Economics and Policy, 10 (1), pp. 68 – 88.
[31] Barla, P., Lamonde, B., Miranda-Moreno, L. and Boucher, N., 2009. Traveled Distance, Stock and Fuel Efficiency of Private Vehicles in Canada: Price Elasticities and Rebound Effect. Transportation 36 (4):389-402.
[32] EIA Annual Energy Review, various editions. For data 2012-2014, and projected data: EIA Annual Energy Outlook (AEO) 2016 (Reference Case). See Table 11, file "aeotab_11.xls."
[33] EIA Annual Energy Outlook 2016, Table 11, aeotab_11.xlsx.
[34] See EIA Annual Energy Review, various editions. For data 2012-2014, and projected data: EIA Annual Energy Outlook (AEO) 2016 (Reference Case). See Table 11, file "aeotab_11.xls."
[35] U.S. EIA, 2016. "Canada provides record-high share and amount of U.S. crude oil imports in 2015," April 12, 2016. http://www.eia.gov/todayinenergy/detail.php?id=25772.
[36] EIA Annual Energy Outlook 2016, Table 21, yearbyyear.xlsx.
[37] Based on data from the CIA Factbook, which combines data from various recent years, https://www.cia.gov/library/publications/the-world-factbook/rankorder/2242rank.html. Accessed 10.19/2016.
[38] IEA 2011 "IEA Response System for Oil Supply Emergencies." [EPA-HQ-OAR-2014-0827-0573].
[39] We looked at changes in U.S. crude oil imports and net petroleum products in the AEO 2015 Reference Case in comparison the Low (i.e., Economic Growth) Demand Case to undertake this analysis. See the spreadsheet "Impact of Fuel Demand on Imports AEO2015.xlsx." We also considered a paper entitled "Effect of a U.S. Demand Reduction on Imports and Domestic Supply Levels" by Paul Leiby, 4/16/2013. This paper suggests that "Given a particular reduction in oil demand stemming from a policy or significant technology change, the fraction of oil use savings that shows up as reduced U.S. imports, rather than reduced U.S. supply, is actually quite close to 90 percent, and probably close to 95 percent." [EPA-HQ-OAR-2014-0827-0572] [EPA-HQ-OAR-2014-0827-0574].
[40] Leiby, Paul N., Donald W. Jones, T. Randall Curlee, and Russell Lee, 1997, *Oil Imports: An Assessment of Benefits and Costs*, ORNL-6851, Oak Ridge National Laboratory, [EPA-HQ-OAR-2014-0827-0594].
[41] Leiby, P., Factors Influencing Estimate of Energy Security Premium for the GHG Program, Oak Ridge National Laboratory. [EPA-HQ-OAR-2014-0827-0595].
[42] Brown, S. and Huntington, H., 2013, Assessing the U.S. Oil Security Premium, Energy Economics, vol. 38, pp. 118 - 127. [EPA-HQ-OAR-2014-0827-0571].
[43] Brown, S. and Huntington, H., 2010, Reassessing the Oil Security Premium. RFF Discussion Paper Series, (RFF DP 10-05). doi: RFF DP 10-05 [EPA-HQ-OAR-2014-0827-0602].
[44] Greene, D., 2010, Measuring energy security: Can the United States achieve oil independence? Energy Policy, 38(4), 1614–1621. EPA-HQ-OAR-2014-0827-0576].
[45] Toman, M., 1993, The economics of energy security: theory, evidence and policy, Chapter 25, Handbook of Natural Resource and Energy Economics, Volume 3, pp. 1167-1218.
[46] Ledyard, J. O. "Market Failure." The New Palgrave Dictionary of Economics. Second Edition. Eds. Steven N. Durlauf and Lawrence E. Blume. Palgrave Macmillan, 2008. [EPA-HQ-OAR-2014-0827-0596].
[47] Sivaram, Varun; Levi, Michael A., 2015, "Automobile Fuel Standards in Lower-Oil-Price World," Council on Foreign Relations.
[48] National Academy of Sciences, 2015, "Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," Committee on the Assessment of Technologies for Improving Fuel, Economy of Light-Duty Vehicles, Phase 2; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Research Council.
[49] Gately, D., 2004, "OPEC's Incentives for Faster Output Growth," The Energy Journal, 25 (2):75-96; Gately, D., 2007. "What Oil Export Levels Should We Expect From OPEC?" The Energy Journal*,* 28(2):151-173. [EPA-HQ-OAR-2014-0827-0599].

[50] Drabik, D. and de Gorter, H., 2011, "Biofuel Policies and Carbon Leakage", AgBioForum, 14(3): 104-110
[51] Rajagopal, D., Hochman, G. and Zilberman, D., 2011, "Indirect fuel use policies (IFUC) and the lifecycle environmental impact of biofuel policies", Energy Policy, 39: 228-233.
[52] Thompson, W., Whistance, J. and Meyer, S., 2011, "Effects of U.S. biofuel policies on U.S. and world petroleum product markets and consequences for greenhouse gas emissions", Energy Policy, 39: 5509-5518.
[53] Erickson, P. and Lazarus, M., 2014, "Impact of Keystone Pipeline on global oil markets and greenhouse gas emissions", Stockholm Environmental Institute.
[54] Karplus, V., Kishimoto, P. and Paltsev, S., 2015, "The Global Energy, CO_2 Emissions and Economic Impacts of Vehicle Fuel Economy Standards", Journal of Transport Economics and Policy, 49(4): 517-538.
[55] Historical data are from EIA Annual Energy Review, various editions. For data since 2012 and projected data: source is EIA Annual Energy Outlook (AEO) 2015 (Reference Case). See Table 11, file "aeotab_11.xlsx" and Table 20 (Macroeconomic Indicators," (file "aeotab_20.xlsx"). [EPA-HQ-OAR-2014-0827-0619].
[56] Bohi, D. and Montgomery, D., 1982. Social Cost of Imported and U.S. Import Policy, Annual Review of Energy, 7:37-60. Energy Modeling Forum, 1981. World Oil, EMF Report 6 (Stanford University Press: Stanford 39 CA. https//emf.stanford.edu/publications/emf-6-world-oil.
[57] Plummer, J. (Ed.), 1982. Energy Vulnerability, "Basic Concepts, Assumptions and Numerical Results," pp. 13 - 36, (Cambridge MA: Ballinger Publishing Co.). [EPA-HQ-OAR-2014-0827-0600].
[58] Bohi, D., and Montgomery, D., 1982, Social Cost of Imported and U.S. Import Policy, Annual Review of Energy, 7:37-60.
[59] Hogan, W., 1981, "Import Management and Oil Emergencies," Chapter 9 in Deese, 5 David and Joseph Nye, eds. Energy and Security. Cambridge, MA: Ballinger Publishing Co. [EPA-HQ-OAR-2014-0827-0578].
[60] Broadman, H. G. 1986, "The Social Cost of Imported Oil," Energy Policy 14(3):242-252. Broadman H. and W. Hogan, 1988. "Is an Oil Import Tariff Justified? An American Debate: The Numbers Say 'Yes'." The Energy Journal 9: 7-29. [EPA-HQ-OAR-2014-0827-0569] [EPA-HQ-OAR-2014-0827-0570].
[61] Leiby, P., Jones, D., Curlee, R. and Lee, R., Oil Imports: An Assessment of Benefits and Costs, ORNL-6851, Oak Ridge National Laboratory, 1997. [EPA-HQ-OAR-2014-0827-0594].
[62] Parry, I. and Darmstadter J., 2004, "The Costs of U.S. Oil Dependency," Resources for the Future, November 17, 2004 (also published as NCEP Technical Appendix Chapter 1: Enhancing Oil Security, the National Commission on Energy Policy 2004 Ending the Energy Stalemate - A Bipartisan Strategy to Meet America's Energy Challenges). [EPA-HQ-OAR-2014-0827-0603].
[63] National Research Council, 2009, Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use. National Academy of Science, Washington, DC. [EPA-HQ-OAR-2014-0827-0597].
[64] See, William Nordhaus, "Who's Afraid of a Big Bad Oil Shock?" and Blanchard, O. and Gali, J., "The macroeconomic Effects of Oil price Shocks: Why are the 2000s so different from the 1970s?," pp. 373-421, in The International Dimensions of Monetary Policy, Gali, J., and Gertler, M., editors, University of Chicago Press, February 2010, available at http://www.nber.org/chapters/c0517.pdf [EPA-HQ-OAR-2014-0827-0567].
[65] Blanchard, O. and Gali, J., pp. 414. [EPA-HQ-OAR-2014-0827-0568].
[66] See, Oil Price Drops on Oversupply, http://www.oil-price.net/en/articles/oil-price-drops-on-oversupply.php, 10/6/2014. [EPA-HQ-OAR-2014-0827-0566].
[67] Hamilton, J. D., 2012, Oil Prices, Exhaustible Resources, and Economic Growth. In Handbook of Energy and Climate Change. Retrieved from http://econweb.ucsd.edu/~jhamilto/handbook_climate.pdf [EPA-HQ-OAR-2014-0827-0577].
[68] Ramey, V. and Vine, D., 2010, "Oil, Automobiles, and the U.S. Economy: How Much have Things Really Changed?" National Bureau of Economic Research Working Papers, WP 16067. Retrieved from http://www.nber.org/papers/w16067.pdf [EPA-HQ-OAR-2014-0827-0601].
[69] Baumeister, C., Peersman, G., Van Robays, I., 2010, "The Economic Consequences of Oil Shocks: Differences across Countries and Time", Workshop and Conference on Inflation Challenges in the Era of Relative Price Shocks.
[70] Kilian, L., Vigfusson, R., 2014, "The Role of Oil Price Shocks in Causing U.S. Recessions", Board of Governors of the Federal Reserve System. International Finance Discussion Papers.
[71] Cashin, P., Mohaddes, K., and Raissi, M., 2014, "The differential effects of oil demand and supply shocks on the global economy." Energy Economics.
[72] Batovic, A., 2015, Low oil prices fuel political and economic instability. *Global Risk Insights*, 18–19. Retrieved from http://globalriskinsights.com/2015/09/low-oil-prices-fuel-political-and-economic-instability/.
[73] Monaldi, F., 2015, The Impact of the Decline in Oil Prices on the Economics, Politics and Oil Industry of Venezuela. *Columbia Center on Global Energy Policy Discussion Papers*, (September). Retrieved from

http://energypolicy.columbia.edu/sites/default/files/energy/Impact of the Decline in Oil Prices on Venezuela, September 2015.pdf.
[74] Even, S., & Guzansky, Y., 2015, Falling oil prices and Saudi stability - Opinion. *Jerusalem Post*, (September 30). Retrieved from http://www.jpost.com/Opinion/Falling-oil-prices-and-Saudi-stability-419534.
[75] International Monetary Fund (IMF), 2015, *IMF Regional Economic Outlook - Middle East and Central Asia*. *Regional Economic Outlook* (Vol. 33). Tomkiw, L., 2015, Oil Rich Saudi Arabia Running Out Of Assets? IMF Report Says It's Possible In Next 5 Years. *International Business Times*, *October 21*, 19–22. Retrieved from http://www.ibtimes.com/oil-rich-saudi-arabia-running-out-assets-imf-report-says-its-possible-next-5-years-215017.
[76] Crane, K., Goldthau, A., Toman, M., Light, T., Johnson, S., Nader, A., Rabasa, A. and Dogo, H., Imported oil and U.S. national security. RAND Corporation, 2009, http://www.stormingmedia.us/62/6279/A627994.pdf.
[77] Koplow, D., and Martin, A., 1998, Fueling Global Warming: Federal Subsidies to Oil in the United States. Greenpeace, Washington, DC.
[78] Crane et al., 2009, "Imported Oil and U.S. National Security", RAND Corporation.
[79] Moore, J., Behrens, C., and Blodgett, J., "Oil Imports: An Overview and Update of Economic and Security Effects." CRS Environment and Natural Resources Policy Division report 98, no. 1 (1997): 1-14.
[80] Copulos, M. "America's Achilles Heel: The Hidden Costs of Imported Oil." Alexandria VA: The National Defense Council Foundation, September (2003): 1-153. Copulos, M., "The Hidden Cost of Imported Oil--An Update." The National Defense Council Foundation (2007). Delucchi, Mark A. and James J. Murphy. "US military expenditures to protect the use of Persian Gulf oil for motor vehicles." Energy Policy 36, no. 6, 2008: 2253-2264, Crane et al. /RAND, as above, Stern, Roger J. "United States cost of military force projection in the Persian Gulf, 1976–2007." Energy Policy 38, no. 6 (June 2010): 2816-2825. http://linkinghub.elsevier.com/retrieve/pii/S0301421510000194.
[81] "Transitions to Alternative Vehicles and Fuels," Committee on Transitions to Alternative Vehicles and Fuels, National Research Council, 2013.
[82] Fann, N., Baker, K.R., and Fulcher, C.M. (2012). *Characterizing the PM2.5-related health benefits of emission reductions for 17 area and mobile emission sectors across the U.S.*, Environment International, 49, 241-151, published online September 28, 2012.
[83] U.S. Environmental Protection Agency (U.S. EPA). (2016). *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles - Phase 2: Regulatory Impact Analysis*, Assessment and Standards Division, Office of Transportation and Air Quality, EPA-420-R-16-900, August 2016.
[84] U.S. Environmental Protection Agency (U.S. EPA). (2012*). Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards*, Assessment and Standards Division, Office of Transportation and Air Quality, EPA-420-R-12-016, August 2012. Available on the Internet at: http://www.epa.gov/otaq/climate/documents/420r12016.pdf.
[85] U.S. Environmental Protection Agency (U.S. EPA). (2013). *Regulatory Impact Analysis for the Reconsideration of the Existing Stationary Compression Ignition (CI) Engines NESHAP*, Office of Air Quality Planning and Standards, Research Triangle Park, NC. January. EPA-452/R-13-001. Available at http://www.epa.gov/ttnecas1/regdata/RIAs/RICE_NESHAPreconsideration_Compression_Ignition_Engines_RIA_final2013_EPA.pdf.
[86] U.S. Environmental Protection Agency (U.S. EPA). (2013). *Regulatory Impact Analysis for Reconsideration of Existing Stationary Spark Ignition (SI) RICE NESHAP*, Office of Air Quality Planning and Standards, Research Triangle Park, NC. January. EPA-452/R-13-002. Available at http://www.epa.gov/ttnecas1/regdata/RIAs/NESHAP_RICE_Spark_Ignition_RIA_finalreconsideration2013_EPA.pdf.
[87] U.S. Environmental Protection Agency (U.S. EPA). (2015). *Regulatory Impact Analysis for Residential Wood Heaters NSPS Revision*. Office of Air Quality Planning and Standards, Research Triangle Park, NC. February. EPA-452/R-15-001. Available at http://www2.epa.gov/sites/production/files/2015-02/documents/20150204-residential-wood-heaters-ria.pdf.
[88] U.S. Environmental Protection Agency. (2012). *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter*, Health and Environmental Impacts Division, Office of Air Quality Planning and Standards, EPA-452-R-12-005, December 2012. Available on the internet: http://www.epa.gov/ttnecas1/regdata/RIAs/finalria.pdf.
[89] Fann, N., Baker, K.R., and Fulcher, C.M. (2012). *Characterizing the PM2.5-related health benefits of emission reductions for 17 industrial, area and mobile emission sectors across the U.S.*, Environment International, 49, 241-151, published online September 28, 2012.

---

[90] U.S. Environmental Protection Agency (U.S. EPA). (2009). Integrated Science Assessment for Particulate Matter (Final Report). EPA-600-R-08-139F. National Center for Environmental Assessment—RTP Division. December. Available at http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=216546.
[91] U.S. Environmental Protection Agency. (2012). *Regulatory Impact Analysis for the Final Revisions to the National Ambient Air Quality Standards for Particulate Matter*, Health and Environmental Impacts Division, Office of Air Quality Planning and Standards, EPA-452-R-12-005, December 2012. Available on the internet: http://www.epa.gov/ttnecas1/regdata/RIAs/finalria.pdf.
[92] Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866, Interagency Working Group on Social Cost of Greenhouse Gases, with participation by Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Interior, Department of Transportation, Department of the Treasury, Environmental Protection Agency, National Economic Council, Office of Management and Budget, Office of Science and Technology Policy (May 2013, Revised August 2016). Available at: < https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc_tsd_final_clean_8_26_16.pdf > Accessed 10/20/2016.
[93] See https://www.whitehouse.gov/omb/oira/social-cost-of-carbon for both TSDs.
[94] See July 2015 Response to Comments document on the SCC, https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-response-to-comments-final-july-2015.pdf. See also (1) Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act, 74 Fed. Reg. 66,496, 66,535 (Dec. 15, 2009) and (2) National Research Council. 2013. Climate and Social Stress: Implications for Security Analysis. National Academies Press. Washington, DC.
[95] Clean Power Plan final rule, see 80 FR 64661; 10/23/15.See also Clean Power Plan Response to Comments, Section 8.7.2, Document ID EPA-HQ-OAR-2013-0602-37106.
[96] U.S. Environmental Protection Agency (U.S. EPA). 2012. Regulatory Impact Analysis Final New Source Performance Standards and Amendments to the National Emissions Standards for Hazardous Air Pollutants for the Oil and Natural Gas Industry. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. April. < http://www.epa.gov/ttn/ecas/regdata/RIAs/oil_natural_gas_final_neshap_nsps_ria.pdf >.
[97] Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under : Executive Order 12866, Interagency Working Group on Social Cost of Greenhouse Gases, with participation by Council of Economic Advisers, Council on Environmental Quality, Department of Agriculture, Department of Commerce, Department of Energy, Department of Interior, Department of Transportation, Department of the Treasury, Environmental Protection Agency, National Economic Council, Office of Management and Budget, Office of Science and Technology Policy (August 2016). Available at: < https://www.whitehouse.gov/sites/default/files/omb/inforeg/august_2016_sc_ch4_sc_n2o_addendum_final_8_26_16.pdf> Accessed 10/20/2016.
[98] Marten, A. L., E. A. Kopits, C. W. Griffiths, S. C. Newbold & A. Wolverton (2014, online publication; 2015, print publication). Incremental CH4 and N2O mitigation benefits consistent with the U.S. Government's SC-CO2 estimates, Climate Policy, DOI: 10.1080/14693062.2014.912981.
[99] Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
[100] For example, see (1) U.S. Environmental Protection Agency (U.S. EPA). (2012). Regulatory Impact Analysis: Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, Assessment and Standards Division, Office of Transportation and Air Quality, EPA-420-R-12-016, August 2012. Available on the Internet at: http://www.epa.gov/otaq/climate/documents/420r12016.pdf. and (2) U.S. Environmental Protection Agency (U.S. EPA). 2012. Regulatory Impact Analysis Final New Source Performance Standards and Amendments to the National Emissions Standards for Hazardous Air Pollutants for the Oil and Natural Gas Industry. Office of Air Quality Planning and Standards, Health and Environmental Impacts Division. April. < http://www.epa.gov/ttn/ecas/regdata/RIAs/oil_natural_gas_final_neshap_nsps_ria.pdf >.
[101] See "Auto Loan Rates for Use in the OMEGA ICBT," memorandum from Todd Sherwood, Assessment and Standards Division, Office of Transportation and Air Quality, dated November 15, 2016.

Table of Contents

Table of Figures

Table of Tables

Chapter 4: Consumer Issues

This chapter supplements Section B.1 of the Appendix to the Proposed Determination document, which examines consumer acceptance of vehicles subject to the standards. It begins in Chapter 4.1 with a discussion of the possibility of tradeoffs between fuel economy and other vehicle attributes, related to the discussion in Appendix Section B.1.4. The key questions include whether those tradeoffs exist, whether they can be measured if they do exist, and how vehicle buyers might evaluate those tradeoffs if they exist. Chapter 4.2 supplements the Proposed Determination document Appendix Sections B.1.2., B.1.3., and B.1.5. with a discussion of a recent study of the effects of the standards on vehicle sales and employment, and elaboration on the discussion of whether the technologies used to meet the standards impose "hidden costs" on vehicle buyers. Finally, Chapter 4.3 provides greater detail on the analysis of vehicle affordability discussed in the Proposed Determination document Appendix Section B.1.6.

4.1 Potential Existence of Tradeoffs between Fuel Economy and Other Vehicle Attributes

Section B.1 of the Appendix to the Proposed Determination document discusses consumer response to the standards. In particular, it examines concerns over the effects of the standards on sales, and whether other vehicle attributes, such as power, may be adversely affected by standards (see especially Section B.1.4). This subchapter discusses issues related to the potential existence of tradeoffs between fuel economy and other vehicle attributes. We begin with a brief discussion of the reference case, including the assumption that the fleet's fuel economy will not increase in the absence of the standards, and then proceed to a discussion of the effects of the standards on other attributes.

4.1.1 The Reference Case

For this Proposed Determination, EPA is assuming that the MY2022-2025 reference fleet will have GHG emissions performance equal to that necessary to meet the MY2021 standards (in effect a "flat" reference fleet). This is consistent with the assumption used in the MY2017-2025 rulemaking, where EPA presented a detailed rationale for assuming that there would be no decrease in fleetwide GHG emissions performance in the reference case fleet for MY2017-2025 beyond the GHG emissions performance necessary to meet the MY2016 standards.[1] Key elements of the rationale were: 1) projections that gasoline prices would be relatively stable out to 2025, 2) historical evidence that during periods of stable gasoline prices and fuel economy standards, the only companies that typically over-complied with fuel economy standards were those that produced primarily lighter vehicles that inherently over-complied with the older universal (one size fits all, non-attribute based) fuel economy standards, 3) that under increasingly stringent footprint-based GHG and fuel economy standards for the five years from MY2012-2016, it was likely that most major manufacturers would be constrained by the standards and unlikely to voluntarily over-comply, and 4) if there were individual manufacturer over-compliance in a reference case scenario, that manufacturer would likely generate credits that could be sold to other companies, and therefore not lead to fleetwide over-compliance.

EPA believes that the case for a flat GHG reference case fleet is even stronger for the MY2022-2025 timeframe for the following reasons: 1) gasoline prices are about $1 per gallon lower today than in October 2012 when the MY2017-2025 final rule was published, 2) AEO 2016 reference case projections for fuel prices in the MY2022-2025 timeframe are relatively stable and approximately $1 per gallon lower than the AEO 2012 Early Release projections upon which we relied in the final rulemaking analysis, 3) another five years of increasingly stringent footprint-based GHG and fuel economy standards under the National Program (i.e., the MY2022-2025 reference case fleet must meet the MY2021 standards, five years later than the MY2016 standards which were the basis for the MY2017-2025 reference case fleet) that will have led to significant commercialization of new technologies, and 4) due to the additional five years of increasingly stringent standards, credits generated in the MY2022-2025 timeframe are likely to be even more valuable, and even more likely to be sold, than in the MY2017-2021 timeframe. For all of these reasons, EPA believes that it is very unlikely that there would be any market-driven decrease in fleetwide GHG emissions performance (i.e., overcompliance) in a MY2022-2025 reference case fleet.

As discussed in Chapter 1 of this TSD, EPA's reference fleet assumes that, while relative production volumes will continue to evolve through 2025, all characteristics of individual vehicle models and configurations, except GHG emissions and fuel economy driven by the standards, will remain unchanged through 2025. In other words, for purposes of assessing the regulatory impacts analysis of the MY2022-2025 standards, and for properly accounting for the cost of the additional technology required to meet those standards, EPA is making the modeling assumption that added technology will be used to reduce greenhouse gas emission and not to improve vehicle performance and utility. It is important to note that the cost estimates include the costs of maintaining those other vehicle attributes, so that there is no reduction in vehicle quality. EPA used a similar approach in the 2012-2016 and the 2017-2025 rulemakings (see, e.g., 77 FR at 62840/3), and in the Draft TAR. Nevertheless, it is possible that automakers, in the absence of these standards, would instead have invested in enhancing vehicle attributes such as power, with an explicit tradeoff between those enhancements and reducing fuel consumption and GHG emissions. If manufacturers may have chosen to apply technology to improve vehicle performance in lieu of efficiency, the standards may result in higher costs than projected in this analysis. This subchapter provides a discussion of that assumption.

Regarding the general issue of constant vehicle characteristics, the National Research Council[2] in its 2015 report stated that assuming equivalent performance in the fleet "is equivalent to a reference case with no further technical change in the vehicle market from 2017 to 2025." This, it stated, is inconsistent with past trends, where "the rate of technological progress in vehicle attributes and efficiency has been strong and continual over the past 30 years." From the 1980s to about 2005, as described in Chapter 3.1.5 of the Draft TAR, horsepower and weight increased steadily, while fuel economy was either stable or declining. The NRC suggests developing a reference case that reflects technological progress over time, and its possible allocation to horsepower and weight, rather than assuming equivalent performance. Specifically, the NRC recommended:

"Recommendation 10.7: The agencies should consider how to develop a reference case for the analysis of societal costs and benefits that includes accounting for the potential opportunity costs of the standards in terms of alternative vehicle attributes forgone."[3]

The technological progress referred to by the NRC has been an ongoing process in the auto industry. Several recent studies,[4] discussed in Chapter 4.1.2 below, have sought to estimate the magnitude of innovation by calculating the relationship between power, fuel economy, and weight each year. Over time, if it is possible to have more fuel economy for a constant amount of power and weight (or more power or weight for constant fuel economy), those studies define that increase as innovation. These studies argue that most of that innovation has in the past gone into improvements in vehicle power. The authors expect that the vehicle GHG and fuel economy standards are instead directing that innovation toward fuel economy. As a result, because technological innovation has not been directed toward power, vehicles in the reference case must be less powerful than they would be in the absence of the standards. Thus, such studies would suggest that the reference case should be revised to project that power would have been higher; if vehicles subject to the standards do not achieve that new reference-case level of power, then the agencies should account for the opportunity cost of the forgone power.

In contrast, a working paper from Cooke[5] argues that the reference case should not include these presumed increases in power or other attributes, because the agencies are not required to do more than preserve the baseline attributes. Cooke argues that increases in power or other vehicle attributes are optional to manufacturers, and thus not the responsibility of the agencies. If those technologies were instead applied to vehicle performance or other attributes rather than fuel economy, and it then becomes more expensive to meet the standards, Cooke argues that that increase in costs is properly attributable to a discretionary decision, not to the standards.

EPA also received comments from UCS recommending that EPA create a baseline equivalent to the 2014 baseline with 2010 MY vehicles, using engineering judgment to assess what technologies are applied to the vehicle, because updating the baseline to post-2010 MYs will fail to account for vehicle manufacturers' choices to apply technology to improve vehicle performance in lieu of improving vehicle efficiency: "Choosing a more recent baseline only further serves to 'bake in' this inefficient use of technology, ascribing costs that should be borne by manufacturers as a trade-off instead as a direct cost of regulation." EPA recognizes that, with each baseline update, some portion of additional technology efficiency is lost to improved vehicle performance. As a result, our calculated cost of compliance is slightly higher than if technologies had been applied only to improve efficiency. Also, the creation of a baseline equivalent to the 2014 model year fleet using 2010 model year vehicles is not possible, in part because there are many vehicles in the 2014 fleet that do not have replacements available in MY2010.

EPA expects that manufacturers will continue to consider ways to improve vehicle utility and performance, and the potential for tradeoffs between reducing GHG emissions and improving other vehicle attributes warrants continued scrutiny. Comments from Resources for the Future argue that methods such as those used in the studies discussed in Chapter 4.1.2 could be used to develop a reference case that would include the potential for improvements over time in vehicle attributes or other attributes associated with improving fuel economy.[A] The analysis of the MY2022-2025 standards would begin with a such a reference case. The cost and effectiveness analysis would involve adding technologies to those new vehicles, either holding those enhanced vehicles' characteristics constant or explicitly acknowledging changes in those characteristics to achieve the standards. In practice, though, estimating these effects and their magnitudes involve

---

[A] As discussed in the Guidelines for Preparing Economic Analyses (U.S. Environmental Protection Agency, 2014, https://yosemite.epa.gov/ee/epa/eed.nsf/webpages/Guidelines.html, Chapter 5), the baseline (referred to in this chapter as the reference case) "is defined as the best assessment of the world absent the proposed regulation or policy action." In other words, the analysis should take into account that change is likely to happen even without the regulation or action.

a number of complexities, including challenges in estimating the tradeoffs and the innovation likely to occur in the absence of the standards, the role of the standards in promoting innovation, and the potential for ancillary benefits associated with GHG-reducing technologies.

The remainder of Chapter 4.1 describes these complexities in more detail. Chapter 4.1.2 focuses on the estimation process mentioned above, for trying to identify expected tradeoffs between fuel economy, power, and weight, and for the measures of innovation. The magnitudes of both the tradeoff estimates and the innovation estimates may not yet be known with confidence. The literature does point to an important aspect of the standards, though: they may increase the amount of innovation over the reference-case level. Chapter 4.1.3 examines this question more closely. In particular, it draws on the literature on innovation to distinguish between "incremental," small-scale innovation, and "major" innovation. It proposes a thesis that incremental technology is likely to be what would happen in the absence of the standards, while the standards may trigger major technology. If so, both the benefits and the costs of major innovation are associated with the standards. If incremental innovation can happen irrespective of the standards – that is, the benefits and costs of incremental innovation are unaffected by the standards – then the only tradeoffs important for the standards are those associated with major innovations. While Chapter 4.2.2 discusses recent EPA research exploring whether there are possible adverse effects of fuel-saving technologies, Chapter 4.1.4 points out that some of these technologies have ancillary benefits. Finally, Chapter 4.1.5 discusses how EPA might evaluate the impact of the standards on other vehicle characteristics in the benefit-cost analysis.

4.1.2 Recent Studies of the Engineering Tradeoffs between Power and Fuel Economy, and Increases in Innovation

The recent studies[6] that estimate both technological improvements over time in the auto industry, as well as the engineering tradeoffs among fuel economy, power, and weight (and sometimes other characteristics) have much in common with each other. They all estimate an equation roughly of the form,

$$\ln(\text{fuel economy}) = \beta0 + \beta1*\ln(\text{horsepower}) + \beta2*\ln(\text{weight}) + \beta4*\text{Other Characteristics} + \varepsilon,$$

where:

ln refers to the natural logarithm of the term in parentheses,

βs are coefficients to be estimated in the statistical analysis (and measure elasticities of fuel economy with respect to its associated variable)

ε is an error term

They differ in the additional vehicle characteristics that they include in the regressions, and in their ways of measuring technological change. Estimates of the elasticities of fuel economy with respect to horsepower–that is, the engineering tradeoffs between fuel economy and horsepower–include values from -0.16 (Klier and Linn) to -0.32 (Knittel 2011); the elasticities between fuel economy and weight include values from -0.336 (Klier and Linn 2016) to -0.521 (MacKenzie and Heywood 2015).[B]

Regarding measures of technological change, Knittel (2011) and MacKenzie and Heywood (2015) use annual shifts in the tradeoff curves; Klier and Linn (2016) use engine redesign cycles for individual vehicles; and Wang (2016) uses a time trend and the level (stringency) of fuel economy standards. The papers all find technological innovation, defined as an increase over time in fuel economy not explained by changes in horsepower, weight, or other characteristics, to be ongoing. Knittel (2011) finds truck and car efficiency to have increased about 50 percent from 1980 to 2006, with innovation higher before 1990 than in subsequent years. MacKenzie and Heywood find that efficiency measured using horsepower and weight increased about 50 percent from 1975-2009, but nearly 60 percent using acceleration and weight; using acceleration, features, and functionality led to an estimate of 70 percent improvement. Klier and Linn (2016) find that technological innovation varies with the stringency of predicted standards and with the enactment of new standards but do not provide estimates of the magnitudes of baseline innovation. Wang (2016) finds that cars innovated 1.19 percent per year, and trucks 0.66 percent per year from 1975 to 2011; a 1 percent increase in CAFE standards led to an additional increase of 0.32 percent in innovation for cars, and 0.62 percent for trucks. These last two studies argue that GHG and fuel economy standards increase technological innovation above levels without regulation.

MacKenzie and Heywood (2015) raise questions with the approach adopted by many of these studies (focusing on Knittel 2011). In particular, they argue that horsepower and weight are not necessarily good proxies for characteristics that consumers want, and that estimates both of the tradeoffs of these characteristics with fuel economy and of technological change are sensitive to the additional vehicle characteristics considered in the regressions.

If horsepower and weight are not themselves of primary interest to vehicle buyers, then, according to MacKenzie and Heywood, the measured tradeoffs of horsepower or weight for fuel economy do not measure changes in metrics important to consumers. Horsepower, for instance, does not by itself measure the full range of performance-related attributes, which include other features such as low-end torque, handling, and acceleration. MacKenzie and Heywood (2012)[7] find that acceleration performance in 2010 is 20 to 30 percent faster than comparable vehicles in the 1970s;[C] in other words, horsepower is not directly proportional to acceleration. Because acceleration is likely to be of more importance to consumers than horsepower itself, the tradeoff for horsepower identified in these analyses may not accurately measure impacts important to consumers.

Similarly, it is unlikely that consumers care directly about vehicle weight; rather, they are probably more interested in size, safety, cargo capacity, or other characteristics that are imperfectly correlated with weight. In these studies, a large vehicle with significant mass

---

[B] The papers include multiple specifications: they may include different regressions for different vehicle classes, a variety of additional covariates, or different functional forms. Some of the studies include torque or zero-to-60 times instead of or in addition to horsepower. The values given here are from comparing preferred specifications specifically using horsepower and weight. The values in different specifications include values within and outside these ranges; the ranges cited here thus potentially understate the variation in point estimates.

[C] They attribute this change to improvements in the transformation of engine power to acceleration.

reduction and improved fuel economy would show up in the data to have the same attributes as a smaller efficient car, though consumers would view them very differently.

The use of weight and horsepower in these regressions may also bias the estimates of technological change. In these studies, technological change is measured as a residual improvement in fuel economy after other factors that influence fuel economy are considered. Including a characteristic (including but not limited to horsepower and weight) in the regressions means that technological change will not affect that characteristic; its fuel economy elasticity is fixed. MacKenzie and Heywood (2015) show this effect by using horsepower in their analysis in one regression, and acceleration (0-to-60 time) in other regressions. When they use acceleration instead of horsepower, the amount of technological change due to the relationship between power and acceleration ends up included in their measure of change; that addition increases the estimated level of technological change. They also point out that technological change to reduce weight will not show up as change in these other papers, because, as mentioned above, a large vehicle with mass reduction and improved fuel economy looks in the data like a smaller, efficient car rather than a vehicle with advanced technology.[D]

The measures of technological change are also sensitive to the other characteristics used in the regressions. For instance, Knittel (2011) and Klier and Linn (2016) both include powertrain types as additional characteristics. By assumption, then, powertrain types are not innovations, or subject to innovation; a hybrid or diesel will not become more (or less) efficient relative to a gasoline vehicle over time. [E] MacKenzie and Heywood (2015) argue that an analysis should not include those factors because "shifts toward more inherently efficient powertrain technologies are themselves a part of the overall process of technology change, so it is desirable to capture their contributions to overall efficiency in the year fixed effects" that measure innovation (p. 922).

Recent work by EPA suggests, in addition, that using historic data to estimate tradeoffs may miss changes in the relationship between acceleration and CO2 emissions with new technologies. TSD Chapter 2.3.3.2.1 presents results of using the ALPHA model to examine trade-off curves between CO_2 emissions and 0-to-60 acceleration time for three different engine types: port fuel injection (PFI), gasoline direct injection (GDI), and turbo-downsized (TDS) engines. These engines have different operating efficiency characteristics, and thus different tradeoff curves. Most notably, GDI and TDS, the newer technologies, have much flatter tradeoffs than does the more traditional PFI; in fact, TDS engines reduce CO_2 (albeit only slightly) over a range of 0-to-60 time reductions. Thus, the assumption in the previous research that the tradeoffs among acceleration, fuel economy, and weight are constant does not appear to accurately represent the new technologies, and in fact may substantially overestimate the magnitude of the performance-fuel economy tradeoff.

It is also possible that the estimates for the relationships between fuel economy and other attributes from these studies may not represent pure technology tradeoffs, and may therefore be

[D] In their paper, MacKenzie and Heywood separately apply an adjustment to account for innovations in weight reduction.

[E] Interacting the characteristic with a measure of time allows for innovation specifically in that characteristic; for instance, Knittel interacts the manual transmission variable with a time trend, which allows the fuel consumption of a manual transmission relative to an automatic transmission to vary over time. These papers have few such interactions; this is the only one in Knittel (2011).

biased. Manufacturers do not produce vehicles with all possible combinations of horsepower, fuel economy, and weight; instead, the vehicles they produce include a mix of those characteristics that the companies believe consumers prefer. MacKenzie and Heywood (2015) find that accounting for a vehicle's specific power relative to the specific power of other vehicles in the fleet (the quintile of specific power) affects fuel economy, as well as the responsiveness of fuel economy to acceleration or weight. If these tradeoff curves were purely about technological relationships, they would not be affected by whether a vehicle was relatively powerful, but only by its absolute power. They suggest that "the relative sophistication of a vehicle's engine (compared to others in the same model year) is correlated with weight and acceleration performance; new technologies are not applied uniformly across all vehicles" (p. 922). As a result, the tradeoff estimates may not represent strictly technological tradeoffs, but also manufacturer choices that potentially bias tradeoff estimates.

Based on MacKenzie and Heywood's (2015) work, then, these other studies may not accurately measure tradeoffs involving characteristics of interest to vehicle owners. Weight, for instance, is unlikely to matter to consumers, except if that weight comes from size or added features such as safety. In other work (MacKenzie and Heywood 2012), in which they focus on the relationship between horsepower and acceleration, they question whether improvements in acceleration are going to continue indefinitely; they find that trends in 0-to-60 time are consistent with decay toward an asymptote, and that vehicles in 2010 were within 1 second of the 0-to-60 time asymptotic level.[F] It is not known if this slowdown in acceleration improvements is due to physical limits or limits in consumer interest.

Although MacKenzie and Heywood's (2015) analysis presents a more detailed discussion of these issues compared to the other studies examined here, it is not clear that it is suitable for quantitative development of a new reference case. First, even 0-to-60 time as a measure of acceleration may be too narrow a criterion for evaluating performance. Performance, as a consumer experiences it, is a complex combination of multiple characteristics including initial launch, ability to pass another vehicle at highway speeds, handling, and cornering. Second, as noted above, the analysis in TSD Chapter 2.3.3.2.1 suggests that tradeoff estimates based on historic data may not apply to the newer technologies being implemented. Third, Klier and Linn (2016) and Wang (2016) suggest that the rate of technological innovation is affected by the level of the standards. MacKenzie and Heywood's analysis does not examine this effect. Because of the possibility of a downward bias in innovation from those two studies, their estimates of innovation are not likely to be sufficient. In addition, the standards for MY2012-2025 are more significant in magnitude than any changes since the introduction of CAFE in the late 1970s; it is likely that innovation currently underway in the auto industry is of a different magnitude and kind than in the past. As a result, estimates of innovation from any of these studies may not be applicable to what is currently happening in the auto industry.

4.1.3 <u>The Role of the Standards in Promoting Innovation</u>

As discussed above, some authors point to the role of standards in promoting innovation. This subchapter discusses how innovation may be induced by the standards, and how this innovation

[F] The authors present the analysis, not only for an average vehicle, but also for vehicles in the fifth and ninety-fifth percentiles for acceleration, which all show this flattening.

should be viewed differently in accounting for opportunity costs than innovation that may have occurred in the absence of the standards.

There is a wide body of literature concerning technological change in general.[8] The process of technological change can be divided into three stages: invention, where a new product or process is first developed; innovation, where the product or process is first commercialized; and diffusion, where the product or process is widely adopted throughout an industry. This can be a challenging process: most inventions never make it to the innovation stage;[9] even if they are used by a small number of initial adopters, many technologies never diffuse and thus ultimately fail.[10]

It is generally agreed that innovation – the first commercialization of a new product – occurs on a continuum between two extremes: “major” innovation where product characteristics change, and “incremental” innovation[G] which exploits relatively minor changes to the existing product.[11] Although accurately and completely categorizing innovation may be more complex than applying a simple one-dimensional continuum (as Henderson and Clark (1990) claim), the one-dimensional model does offer some insight into how industries implement innovation.

A good example of a major innovation, and the role of environmental regulations in spurring technology diffusion, is gasoline direct injection (GDI). Mercedes introduced a four-stroke GDI engine into production in 1955.[12] Nonetheless, in 2008, prior to the establishment of the MY2012-2016 standards, only 2 percent of vehicles used gasoline direct injection.[13] By 2015, this number had risen to 42 percent. This changeover shows a major innovation, based on previous inventions, moving from invention to innovation and eventually to diffusion only when stimulated by emissions standards.

As in the GDI example, major innovation does not necessarily proceed immediately (or at all) to diffusion for all promising technologies. In the absence of a forcing mechanism such as regulation, risk-averse manufacturers may prefer smaller, incremental innovations.[14] There are multiple reasons why manufacturers may prefer incremental innovation to major innovation, particularly the risk and uncertainty associated with major innovations.

When a company implements a major innovation, the development costs may be high and the market impacts uncertain. This results in a first-mover disadvantage (see also Section B.1.3.2.3 of the Proposed Determination Appendix), where a pioneer company fronts the bill to test out a new technology. In doing so, it may briefly capture the market, but this allows all other companies to learn about the true demand for the technology without themselves facing any risk.[15] Consumer response to the first mover may give the second mover valuable information about market acceptance. There are, therefore, incentives to delay the development or adoption of a new technology until a competitor has already proven that the technology is profitable. If all producers wait for another one to implement the innovation, the innovation will never enter the market at all.

In addition, Popp et al.[16] point out that there could be “dynamic increasing returns” to adopting some new technologies, wherein the value of a new technology may depend on how many other companies have adopted the technology. This could be due to network effects or

---

[G] Abernathy and Utterback use "major" and "incremental;" Henderson and Clark, with a two-dimensional framework, use "radical" and "incremental."

learning-by-doing. In a network effects situation, the usefulness of the technology depends on adoption of complementary components–for instance, the value of switching to a new fuel depends on the infrastructure available for providing that fuel, and the value of the infrastructure depends on the number of vehicles using the new fuel. Learning by doing (see also Appendix Section A.3.3.3) is the concept that the costs (benefits) of using a particular technology decrease (increase) with use. Both of these incentivize firms to pursue a “wait and see” strategy when it comes to adopting new technologies.

Finally, fixed costs and switchover disruptions[17] delay technology adoption. Firms often face major problems in integrating new technologies resulting from major innovations into their products; in some cases, they may temporarily reduce output.

First-mover disadvantage, dynamic increasing returns, fixed costs, and switchover disruptions all create barriers to major innovation. Incremental innovations typically face less of these problems. Thus, in the absence of a driving factor such as regulation, manufacturers are likely to choose incremental innovations over major innovation.[H]

Both scientific research[18] and popular press[19] suggest that the current light duty GHG standards drive innovation. The mechanism by which the standards affect innovation is the reduction of the barriers to manufacturers for applying major innovation to new vehicles.[I]

Since all manufacturers are required to comply with regulations on the same time schedule, and the technological pace required often outstrips that obtainable by incremental innovation alone, manufacturers are assured that their competition is likely to implement major technological innovations simultaneously. Thus, instead of the first-mover disadvantage, there is a regulation-driven disincentive to “wait and see.” It should be noted that companies differ both in the degree of effort that they face due to the standards, and in the strategies that they choose in response. Nevertheless, the benefits of generating (or avoiding the need for) credits suggest that all companies have incentives to pursue major innovations. In addition, there can be synergies from companies (including suppliers) working on the same technologies at the same time.[20]

Because of the global nature of the auto industry, it is likely that innovations from U.S. regulations are likely to affect vehicles in other countries, and regulations from other countries are likely to affect U.S. vehicles. Because technologies to reduce GHG emissions do not need to be reinvented for each country, the fixed costs of innovation can be spread over a global market. It is even likely that many of these technologies will be used in countries without GHG

[H] This discussion is not intended to imply that major innovation will not happen in the absence of regulation. Many factors affect the likelihood of a technology proceeding from invention through to widespread dissemination, including some degree of luck in having the right invention at the right place at the right time with support from key stakeholders.

[I] The U.S. Department of Energy’s Advanced Technology Vehicles Manufacturing (ATVM) Loan Program provides an example of another mechanism to reduce these barriers. The ATVM provides long-term, low-interest rate loans to support the domestic manufacturing of advanced technology vehicles and automotive components. It can finance a wide range of project costs, including the construction of new manufacturing facilities; retooling, reequipping, modernizing, or expanding an existing facility in the U.S; and the engineering integration costs necessary to manufacture eligible vehicles and components. It is designed to ensure that rising fuel economy standards do not disadvantage domestic manufacturing. With more than $16 billion in remaining loan authority, the ATVM program can provide financing to support the manufacturing of fuel-efficient technologies and components. See http://www.energy.gov/lpo/atvm for more information.

standards, due to the use of common manufacturing platforms across countries and to the ancillary benefits associated with many of these technologies.

Developing a revised reference case could entail estimating *incremental* technological change, and projecting vehicle attributes resulting from that innovation, in the absence of the standards. Developing the control case–the case with the standards in place–could then entail estimating *major* technological change induced by the standards and projections of vehicle characteristics using that greater innovation. The discussion above suggests that conducting such an analysis may involve inaccurate estimates of the amount of innovation both in the absence of and in the presence of the standards, and may provide inaccurate estimates of the consequences of this innovation for specific vehicle characteristics.

Rather than assume a control case with "equivalent performance" to the baseline, one approach could involve assuming a control case with "equivalent performance" to the reference case. Since innovations in the reference case are incremental, such an approach could define, not the reference and control case performance specifically, but rather the difference between them.

In the reference case, it could be assumed that manufacturers would improve vehicle attributes consistent with historical trends due to the implementation of incremental innovations. Some of these changes might affect additional implementation of GHG/fuel economy technologies; in other cases, (for example, infotainment systems, automobile connectivity, or active safety systems), the standards have no or little technical interaction with those changes.

In the control case, it could be assumed that the standards induce major technological improvement used to improve fuel economy. Incremental technological improvement would still be used to improve other vehicle attributes at the same pace as exhibited in the reference case. Thus, the differences between the control and reference cases are both the existence of fuel economy targets and the availability of major technological innovations (in addition to incremental innovations).

It should be noted that there is neither the requirement nor expectation that manufacturers allocate major innovations solely to fuel economy improvement and incremental innovations solely to other vehicle attributes. The standards give manufacturers the flexibility to choose what technologies to apply to which vehicle, when to apply them, and the use of each individual technology. If major innovations driven by the GHG/fuel economy standards were used to enhance these other attributes, though, it should be noted that these other attributes would not have been enhanced in the absence of the standards; those enhancements are ancillary benefits of the standards.

4.1.4 Potential Ancillary Benefits of GHG-Reducing Technologies

Yet another complication associated with assessing an appropriate reference case is the potential existence of ancillary benefits of GHG-reducing technologies. Ancillary benefits can arise due to major innovation enabling new features and systems that can provide greater comfort, utility, or safety.[J] The studies discussed above all assume that, other than through

[J] It is also possible that these new technologies may have undesirable adverse effects – hidden costs – associated with them, such as noise or vibration. EPA's analysis to identify hidden costs through review of professional auto innovation, improving fuel economy reduces power or weight, and thus imposes opportunity costs; and innovation can be channeled only to fuel economy, weight, or some single-dimensional measure of performance, such as 0-60 acceleration. When performance is characterized more broadly as a combination of multiple characteristics, it will often not be possible to strictly maintain performance along every dimension with the application of technological innovations. For example, a new technology may have unequal effects on the various measures of acceleration performance, so that an attempt to maintain performance along one dimension by resizing the vehicle powertrain will result in an increase or decrease along other dimensions. In addition, some technologies provide ancillary benefits that improve vehicle performance and utility along dimensions that are unrelated to acceleration and powertrain sizing. In such cases, the technologies implemented to reduce GHG emissions enhance other vehicle characteristics, providing entirely new capabilities and desirable features or resulting in lower costs for these features than would be otherwise possible.

Some examples of the potential ancillary benefits of GHG reducing technologies are listed here:

- Mass reduction can provide benefits of improved braking and handling performance, and on towing vehicles can enable additional towing and hauling capability with same or similar engine sizing.
- Mass reduction achieved through material substitution from non-ferrous metals provides greater corrosion resistance.
- Accessory Load reductions achieved through the use of pulse-width modulation (PWM) on accessory motors for HVAC blower fan speeds provide the benefit of improved durability.
- Air conditioning system improvements achieved through variable displacement compressors which adjust automatically rather than shutting off completely provide the benefit of smoother compressor transitions and less noise.
- Advanced transmissions with wider overall gear ratios and lower 1st gear ratios provide the benefit of improved launch feel.
- Electric power steering (EPS) systems enable automakers to implement customer features that utilize automatic steering such as automatic parking features, or trailer hitch connection assistance.
- EPS systems also provide the capability for variable ratio steering systems which allow greater steering responsiveness close to center, and reduced effort at large steering angles, while also reducing the lock-to-lock turns.
- Head-integrated exhaust manifolds and improved thermal management systems reduce warm-up time for the cabin and provide greater passenger comfort in cold climates.
- PEVs which can be remotely activated or programmed to precondition the vehicle in a garage when plugged in provide greater passenger comfort and convenience. In cold weather, the vehicle can be pre-warmed and defrosted, and in warm weather the vehicle can be pre-cooled.

reviews, discussed in Proposed Determination Appendix Section B.1.5.2 and TSD Chapter4.2.2, did not find evidence of systematic hidden costs of the new technologies.

- PEV systems with an electric axle on AWD vehicles, or even each individual wheel with electric drive motors, can provide torque vectoring for improved driving dynamics as the increased torque on the outside wheel is able to steer the car into the corner.
- LED headlights enable adaptive automotive headlight systems, in which lighting intensity and direction can be automatically controlled to road, ambient lighting, and weather conditions.

Additional discussion of the effects of each technology considered in this Proposed Determination is provided in Chapter 2 of this TSD.

4.1.5 Estimating Potential Opportunity Costs and Ancillary Benefits

As discussed above, it is possible that the standards could potentially lead to opportunity costs in terms of reduced power or other adversely affected vehicle attributes. At the same time, the standards may lead to ancillary benefits, perhaps by inducing major innovations that may mitigate or avoid those opportunity costs, or even enhance other attributes. Because the standards may contribute both benefits and costs to other vehicle attributes, measuring the net effect on consumer impacts requires estimates of the values of these attributes to consumers. Although various commenters (the Alliance of Automobile Manufacturers, National Automobile Dealers Association, Resources for the Future, Simmons and Tyner, Global Automakers) emphasize the opportunity costs associated with GHG-reducing technologies, the ancillary benefits have the possibility of being at least as important.

The most common sources of estimates of willingness to pay for these attributes are models developed to understand vehicle purchase decisions. These studies quantitatively estimate the role of various vehicle characteristics, such as size, power, and fuel economy, in those purchase decisions. The parameters estimated for these characteristics can usually be used to derive estimates of the value – the willingness to pay (WTP)--of each attribute to consumers. It is common in this literature, though, for the researchers themselves not to have done the WTP calculation. In a 1988 study, Greene and Liu[21] reviewed the literature to that time; they found, "The dispersion of estimated attribute values both within and across models is striking," varying by factors of 5 to 10 or more; for performance, they considered the variation "wild. . . from -$8 to $4,081 per 0.01 cubic inches per pound." To our knowledge, there has not been a study since that time that has done a comprehensive review of consumers' willingness to pay for vehicle attributes.[K] [22]

EPA commissioned a new review of the literature to understand what is known about consumer valuation of vehicle characteristics.[23] This review is looking at the metrics various studies have considered important for consumer vehicle purchase decisions, and is calculating the WTP values implied by the estimates in those studies. The goal is to determine whether there are robust WTP values that could be used for monetizing at least some of the opportunity costs and ancillary benefits. Though the results are preliminary and have not yet been peer reviewed, they provide some insight into the state of the science on these estimates.

[K] Greene (2010) conducted a review of consumers' willingness to pay for one attribute, fuel economy, and found wide ranges of values.

The analysis has focused on studies from 1995 to present, because of the potential for changes over time in consumer preferences and advances in econometric methods. It also has focused on U.S.-based studies. Fifty-two papers were identified that provided the data to estimate WTP values for the light-duty vehicle market. In most cases, the WTP estimates had to be calculated from statistical results in the papers. The methods are detailed in Greene et al. (2016).

The papers varied in a number of ways. Some used revealed preference data--that is, decisions by individual consumers in actual market settings. Others used aggregate market data on vehicle market shares, prices, and characteristics. Still others used stated preference approaches, in which study participants responded to survey questions. Each of these methods has its advantages and disadvantages. For instance, revealed preference data are based on actual market actions. On the other hand, it is often challenging in these studies to capture all the factors that influence consumer decisions; omissions of key factors may bias the results. In addition, they are not suitable for gauging preferences for novel features that are not yet implemented. In stated preference studies, it is much easier to control precisely for key factors by strategic question designs, but the questions are not based on actual behaviors. Studies also differed in the sources of the data, the time periods of the data, and the statistical tools used to analyze the data.

Each of the papers includes one or more attributes, and one or more sets of results on the role of vehicle attributes in consumer purchase decisions. In addition, for a few attributes such as Vehicle Class, each set of results might contain multiple attributes (e.g., both SUV and compact car). As a result, the 52 papers produced 799 WTP values for 152 unique attributes. Some of these attributes are closely related--for instance, dollars per mile, one measure of fuel consumption, is gallons per mile, another measure of fuel consumption, multiplied by the price of fuel. The study identified 15 categories of attributes, provided in Figure 4.1.

There are several sources of variability or uncertainty in the estimates. First, different studies produce different estimates; indeed, sometimes one study produces multiple estimates. Because these studies use different data and methods, it is not surprising that results differ. If different studies produce similar estimates of WTP, then it is reasonable to consider those values robust. If they produce a wide range of values, then further analysis (called meta-analysis) may identify factors, such as the nature of time period of the data, which affect that range. If patterns are found, then it may be possible to choose factors which are considered to produce more suitable results, and use WTP estimates based on those preferred factors. With the results still preliminary, we have not yet conducted meta-analysis.

Another source of variation in the results is that each estimate of WTP has confidence intervals around it, because they are estimated statistically. In some cases, the variation is also due to variation in the population by factors such as income. Most of the results presented below do not reflect the variation around each estimate, but instead show the variation just in the central estimates. As a result, the variation presented in the results underestimates the full range of the estimates.

Yet another source of variation is the way in which each attribute is measured. For instance, fuel consumption-related measures include miles per gallon, gallons per mile dollars per mile, miles per dollar, and dollars per year. With assumptions about fuel price or other factors, it is possible to convert WTP values for these into the same units. The study has conducted these conversions in some but not all cases.

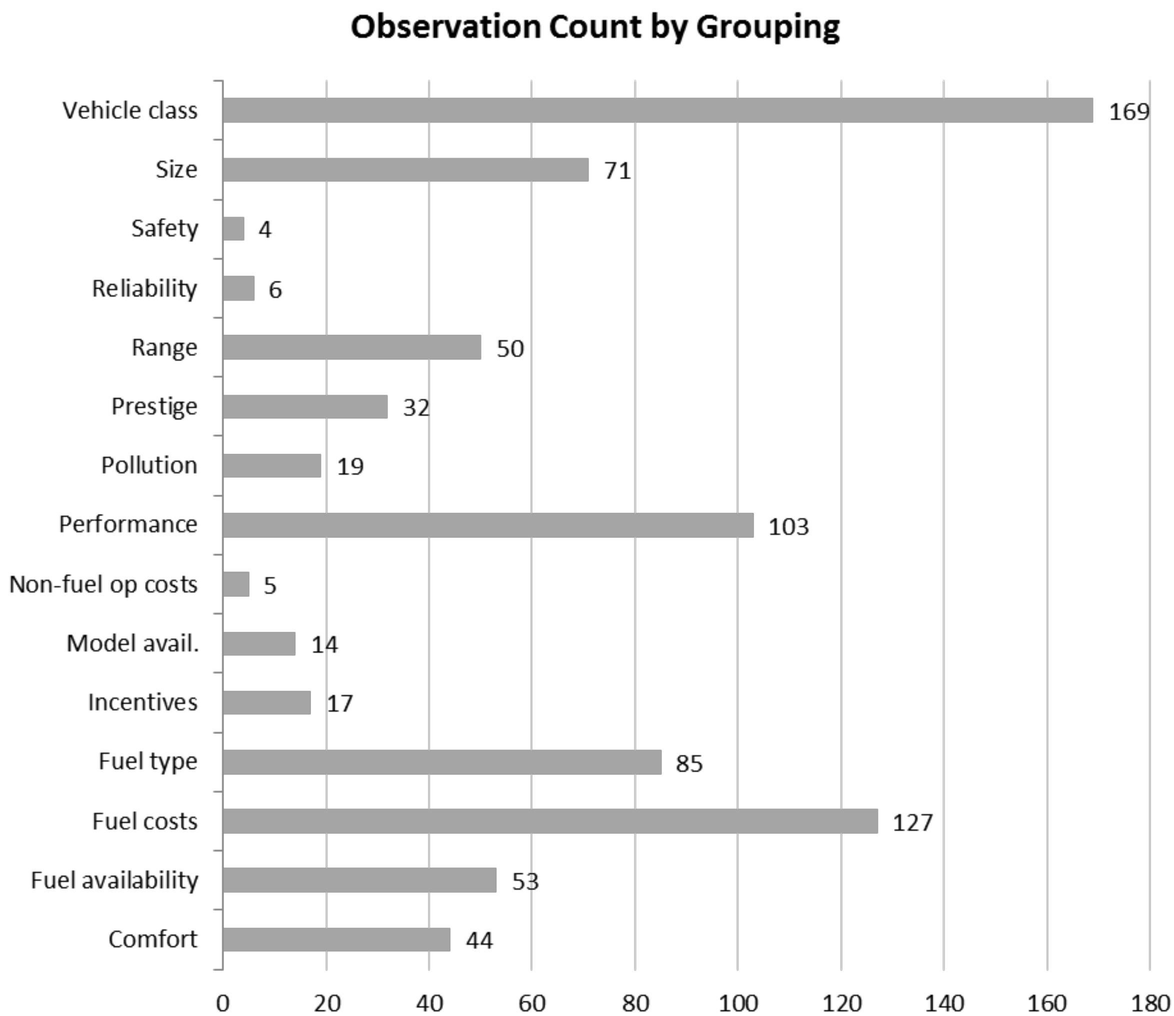


Figure 4.1 Observation Count by Groups of Attributes

Table 4.1 summarizes the results of the study. "Raw" values include all the estimates for each attribute; "trimmed" values remove outliers--values extremely different from others. The mean is the average of all the values. The standard deviation is just of the central estimates--that is, it does not include the variation around each estimate, but rather is just the variation of the central estimates. It thus underestimates the full variation around the estimates. In general, it shows wide variation in the results. For 17 of the 21 attributes using the raw data, the standard deviation is at least as big as the mean. For context, a value is commonly considered to be statistically significantly different from zero if the value is at least 2 standard deviations larger than the mean. Thus, most of these values easily include both negative and positive values as part of their range. For the trimmed values, the standard deviations exceed the means for 13 of the attributes.

Table 4.1 Willingness to Pay (WTP) Estimates from 52 Studies, 2015$.

					Raw		Trimmed		
Grouping	Attribute	N	Units	Out-liers	Mean	SD	Mean	SD	Median
Comfort	Auto-transmission	9	0, 1	1	1,760	3,669	823	2,518	1,111
	Front wheel drive	6	0, 1	0	-3,2031	18,031	-32,031	18,031	-26,779
	Air conditioning	13	0, 1	0	3,521	9,544	3,521	9,544	4,177
	Shoulder room	12	$/inch	1	1,085	1,394	705	479	546
Fuel costs	Cost per mile	58	$/cpm	2	-1,251	3,441	-1,291	1,194	-1,147
	Cost per year	13	$/($/yr)	1	-67	156	-26	50	-6
	Gallons per mile	20	$/0.01gpm	4	14,354	76,395	-7,972	18,740	-580
	Miles per dollar	8	$/(10mi/$)	1	-20,181	27,869	-11,542	14,477	-4,216
	Miles per gallon	10	$/mpg	1	365	659	174	281	64
Fuel type	Electric vehicle	24	0.1	1	-16,515	21,283	-13,851	17,191	-16,837
	Hybrid	28	0, 1	2	-11,727	44,322	-852	18,441	2,796
	Natural gas	7	0, 1	2	-5,620	23,691	6,187	3,851	5,006
Perfor-mance	Acceleration (0-30 mph)	11	$/sec	0	-1,756	1,886	-1,756	1,886	-1,916
	Acceleration (0-60 mph)	8	$/sec	0	-1,096	627	-1,096	627	-1,183
	Horsepower	11	$/hp	4	54	109	13	13	10
	HP/weight	29	0.01hp/lbs	1	1,861	3,523	1,334	2,126	346
	Top speed	9	$/mph	0	100	58	100	58	75
AFV Range	Range	23	$/mi	2	89	41	97	32	98
Size	Footprint	17	$/ft^2	1	43,401	163,103	3,856	4,442	3,273
	Luggage space	12	$/ft^3	1	4,209	9,655	1,445	1,310	1,100
	Weight	19	$/lb	1	10	20	6	8	1

Note: N is the number of observations; Units refers to how the attribute is measured; Mean is the average of central values; SD is the standard deviation of central values; Median is the middle value of the central values. Negative WTP values indicate the WTP for a reduction in the named attribute.

The attributes perhaps of most interest for the purposes of the Proposed Determination are for fuel costs and performance. All the measures of fuel cost show a large variation, spanning positive and negative values, consistent with Greene's (2010) study of WTP for fuel savings.[24] Section B.1.2 of the Proposed Determination Appendix discusses WTP research on fuel economy, and the assertion from various automakers that EPA should use a 2-to-3 year payback period in its modeling of consumer demand for vehicles. A payback period can be roughly converted to a WTP value with a series of assumptions: for instance, the fuel saved in 1 year for a 0.01 gallon/mile reduction in consumption when a vehicle is driven 12,000 miles is 120 gallons; at a fuel price of $2.50/gallon, the value of a change of +0.01 gallons/mile is -$300/year; the present value for two years with a 3 percent discount rate is -$591 (-$580 with a 7 percent discount rate). This study found an average WTP for an increase of 0.01 gallons/mile of $14,354 (standard deviation of $76,395) with the raw data, and -$7,972 (standard deviation of $18,740) with the trimmed data. The positive value for the mean from the raw data suggests that people are willing to pay more to reduce fuel economy, perhaps due to association of fuel economy with other vehicle attributes; this problem with vehicle demand models is discussed in the Proposed Determination Appendix, Section B.1.3.4. The trimmed mean can be converted, using these same assumptions, to an approximate payback period of 54 years with a 3 percent discount rate (essentially an infinite payback period with a 7 percent discount rate). These results suggest that there is in fact not a consensus from the literature around a 2-3 year payback period for the value of fuel savings. As discussed in Section B.1.2 of the Proposed Determination Appendix, and as demonstrated here, the literature instead suggests a very range of payback periods.

For performance, the study included conversions of 0-to-30 acceleration time and horsepower/weight to the metric of 0-to-60 acceleration time. Those combined estimates, even with outliers excluded, ranges from about -$2000/second to +$1000 per second reduction in 0-to-60 time.

As discussed above, these estimates are still preliminary. EPA will conduct further analysis of these results, to investigate whether this variation can be explained in part by the nature of the studies and the data. In the meantime, these results have implications for two aspects of EPA's assessment of the MY2022-2025 standards. First, it seems premature to use these estimates for the values of opportunity costs or ancillary benefits of the standards, because of the very wide ranges, commonly both positive and negative, around the values. The large variation associated with an analysis using those ranges would not be expected to shed much light on the standards; effectively, those values could be either positive or negative. Second, it should be noted that many of these estimates are derived from models of vehicle demand, the same kinds of models that might be used to estimate changes in sales and fleet mix as a result of the standards. The wide ranges of estimates derived from these models suggest that the models themselves are likely to come up with very different responses to the standards. This concern reinforces EPA's decision at this time not to use a vehicle choice model in its modeling for this Proposed Determination. Section B.1.3.4 has further discussion of EPA's consideration of consumer vehicle choice modeling and responses to commenters.

4.2 Consumer Response to Vehicles Subject to the Standards

This subchapter complements the discussions in Sections B.1.3 and B.1.5 of the Proposed Determination Appendix. In particular, it provides further discussion of why EPA is conducting a qualitative, but not a quantitative analysis of the effects of the standards on vehicle sales, and it provides additional findings from our analysis of how professional auto reviewers evaluate the technologies being used to meet the standards.

4.2.1 Impact of the Standards on Vehicle Sales

Section B.1.3 of the Proposed Determination Appendix discusses the potential effects of the standards on vehicle sales. On the one hand, all else equal, higher vehicle costs could lead to depressed sales. On the other hand, all else equal, more efficient vehicles could lead to increased sales. As discussed, there is a wide range of uncertainty about the relative effects of these two factors. In particular, as discussed in Section B.1.2 Appendix and in Chapter 4.1.5 of this TSD, there is a wide range of estimates for the willingness to pay (WTP) for additional fuel economy, as well as for the closely related payback period for fuel economy that consumers use in their purchase decisions. Any estimates of the impacts of the standards on sales must make a series of assumptions on factors such as buyers' WTP for fuel economy and the effects of the standards on vehicle prices. As a result of this uncertainty, EPA has not made a quantitative analysis of the effects of the standards on vehicle sales.

Comments from the Alliance of Automobile Manufacturers, Fiat Chrysler Automobiles, Ford Motor Company, and the National Automobile Dealers Association cite a recent study of the impacts of the standards on vehicle sales, by the Center for Automotive Research (the CAR Report), as a basis for their expressed concerns about the potential impacts of the standards on sales and employment.[25] It demonstrates some of the challenges in conducting such an analysis. It relies on a number of highly questionable assumptions that, if changed, would lead to very different results, as some recent reviews of the CAR Report indicate.[26] As will be outlined below, EPA's assessment of the CAR Report finds that it is significantly flawed in a number of respects, including its excessively high cost estimates that are not based on the costs of technologies for meeting the standards; use of a lower-bound estimate of the fuel savings that consumers will consider in their purchase decisions; econometric models that appear to produce contradictory results; and technical errors, such as comparing costs measured in 2025$ to fuel savings measured in 2015$.

The CAR Report begins with an assumption of technology costs of $2000, $4000, or $6000 per vehicle for a vehicle to go from MY2016 standards to MY2025 standards. It calculates the effects on fuel consumption based on three estimates of fuel prices from the AEO, a 20 percent rebound rate, and the assumption that consumers will consider 3 years of fuel savings in their vehicle purchase decisions. The technology costs with the 3 years of fuel savings subtracted provide an estimate of the increase in expenditures on vehicles. CAR projects a MY2025 average vehicle price so that it can estimate the percent change in the vehicle price. It then uses an elasticity of expenditures with respect to price--the percent change in expenditures associated with the percent change in price--with a projection of sales in the absence of the standards to estimate the effect of the higher costs on expenditures. It then divides expenditures by price to get the estimated effect on vehicle sales. It finds sales effects ranging from an increase of 410,000 to a reduction of 3,710,000, based on different combinations of AEO fuel prices (which affect fuel savings) and up-front costs.

Each of these steps involves questionable assumptions that significantly affect the results, as the following discussion will highlight.

First, CAR's cost assumptions--$2000, $4000, and $6000 per vehicle--are not those of the Draft TAR or any other technology-based analysis. Both Isenstadt (2016) and Cooke (2016) point out that the cost estimates are based on Greene (1991), which estimates the cost of using changes in vehicle prices instead of technology to comply with fuel economy standards.[27] Cooke (2016) observes that Greene (1991) concludes that the pricing scheme is effective for very small changes in fuel economy, but for larger changes, application of technology is less expensive. CAR fails to indicate the dollar years associated with many of its estimates and results. Cooke (2016) assumes that these costs are in 2025$; in 2013$, he estimates that the lowest value used in the CAR Report would be about $1,500, higher than the value in the Draft TAR, $1287 (see Table 12.44, p. 12-35). Isenstadt assumes that the value is in 2010$; if so, it overstates costs even more. Isenstadt further calculates that using the $1,565 cost estimate of the Draft TAR (which he overstates by $279, by including the cost of going from the MY2014 baseline to MY2016 standards) and holding all other assumptions constant would result in a break-even future fuel price of $2.97; any fuel price higher would lead to fuel savings over 3 years exceeding up-front costs.[L] EPA has not independently verified Isenstadt's calculation. Nevertheless, EPA agrees with both these reviewers that the cost estimates in this report, regardless what dollar-year they measure, overestimate the costs of the standards.

This ambiguity over the dollar-year occurs throughout the CAR Report, which does not explain the dollar-year basis for most of its analysis. Cooke (2016) states that the report is inconsistent on the use of real (fixed dollar-year) and nominal (inflation included) dollars; as an example, he notes that gas prices are in real dollars, but are compared to costs in nominal dollars, which he says overestimates payback time by almost 25 percent.

The assumption of 3 years of fuel savings in the CAR Report is based on averaging payback periods for studies that report payback periods in their results. It cites, but does not include in that average, studies that calculate the implicit discount rates that consumers use in their results. Implicit discount rates estimate the interest rates that consumers appear to use in considering the value of future fuel savings over the lifetimes of the vehicles. If the implicit discount rates are approximately the same as interest rates consumers would face for vehicle loans, then it appears that consumers are correctly estimating, and taking into account, the full lifetime of future fuel savings. The studies cited in the CAR Report that provide discount rates find estimates as high as 27 percent, and as low as 3 percent; the low estimates are well within the range of consumer interest rates. In reviewing the literature on the role of fuel savings in vehicle purchases, as discussed in Section B.1.2 of the Proposed Determination Appendix, the National Academy of Sciences finds great variation in the estimates of expected payback periods: "The results of recent studies find that consumers' responses vary from requiring payback in only 2 to 3 years to almost full lifetime valuation of fuel savings" (p. 9-36).[28] Thus, as Cooke (2016) points out, the CAR Report's estimate for the consumer valuation of fuel economy in vehicle purchases is at the very low end of the possible range, in part because it excludes a number of studies from its review (those presenting discount rates instead of payback periods). Higher estimates would increase the relative value of fuel savings and lead to more positive valuation of vehicles subject to the standards.

Cooke (2016) points out another flaw: the Report conflates expenditures on vehicles (price multiplied by quantity) with sales (quantity). In particular, the CAR Report estimates an elasticity of vehicle expenditures with respect to price--the percent change in vehicle expenditures due to a 1 percent change in vehicle price--and then compares that elasticity to estimates in published literature on the demand elasticity--the percent change in sales volume from a 1 percent change in vehicle price.[M] Although the CAR Report claims that its estimated expenditure short-run elasticity, -0.79, is smaller in absolute value than typical results for demand elasticities (of about -1.1), the demand elasticity based on its expenditure elasticity estimate is -1.79, larger in absolute value than typical demand elasticities. As a result, the CAR Report estimates a higher expenditure impact, and thus a higher sales impact, than standard demand elasticities would predict.

[L] Isenstadt (2016) cites the Draft TAR for costs of $1565. This value includes the cost of going from the MY2014 baseline to MY2025, $279, and thus overstates by that much the cost of going from MY2016 standards to MY2025 standards. See Table 12.44, p. 12-35 of the Draft TAR.

[M] Mathematically, the expenditure elasticity is the demand elasticity plus 1.

The CAR Report uses two statistical models to examine the effects of vehicle prices on expenditures. The first (Appendix I) is used to develop the elasticity noted above; the second (Appendix III) is used to project vehicle expenditures in the future in the absence of the standards. They use different data series, and include different independent variables. The effects of vehicle price on expenditures in the two models are opposite: in the first model, price reduces expenditures; in the second model, price increases expenditures. The Report does not explain why it uses different data sources for these two models, both of which are about demand for vehicles, nor why they produce different results. The fact that similar models produce opposite results raises questions about the validity of the models for these purposes.

Because expenditures are price multiplied by quantity, econometric problems may arise by including price as an explanatory variable. Price is not independent of expenditures, as these regression models assume. An increase in vehicle prices may increase expenditures if the increase has a relatively small effect on vehicle sales, or it may decrease expenditures if sales drop significantly; the CAR Report's models produce these two opposite results. In response to changes in vehicle prices, people will change not only the number of vehicles they buy, but also the kinds of vehicles, and thus average vehicle prices. Neither of these models appears to address this complication in the interaction between expenditures and price, and thus neither can be expected to produce accurate estimates of the effects of a price change on expenditures.

The CAR Report estimates employment based on its estimates of the change in vehicle sales.[N] In particular, it estimates employment in the auto industry of 15 workers per domestic vehicle, plus 5.6 additional jobs in the economy per auto industry worker, and 1.3 additional jobs in the economy per dealer employment. The Report does not provide derivations of most of these estimates. Unlike EPA's employment analysis, in Section B.2. of the Proposed Determination Appendix, the CAR Report does not consider possible increases in auto industry sector employment due to development and implementation of fuel-saving technologies, and thus appears to omit some important employment impacts. In addition, as Cooke (2016) points out, this "multiplier" approach to employment analysis does not consider the broader macroeconomic context. As discussed in Section B.2 of the Appendix, when unemployment is low, the primary effect of regulations on overall employment in the economy is to move jobs from some sectors to other sectors, rather than to create or eliminate employment. Multiplier estimates may be useful approximations of employment impacts in a small economy where prices do not adjust; in the U.S. economy, which does not match those characteristics, employment estimates based on multipliers are likely to be overestimates.[29]

Both Isenstadt (2016) and Cooke (2016) suggest that the underlying assumptions of the CAR Report, if changed, would produce very different results, including more scenarios where vehicle sales increase rather than decrease. They also point out that the key assumptions about up-front costs and the payback period for fuel savings that consumers consider in their purchase decisions are at extreme ends of the expected distributions. Even the lowest cost estimate in the Report is higher than estimates in the Draft TAR, and the payback period is at the low end of a large range.

[N] CAR calculates sales by dividing its projected expenditures by a price that it projects assuming a 2.4 percent annual growth in nominal vehicle price per year. The 2.4 percent growth per year is based on a nominal average vehicle price of $24,900 in 2000, and $33,400 in 2015. The growth between those years is actually 2 percent per year.

For these reasons, EPA does not consider the estimates from the CAR Report to provide likely projected impacts of the MY2025 standards.

EPA recognizes the difficulties involved in making reasonable estimates of these projections. As discussed above and in Section B.1.3. of the Proposed Determination Appendix, on the one hand, the vehicles designed to meet the standards will become more expensive, which would, by itself, discourage sales; on the other hand, the vehicles will have improved fuel economy and thus lower operating costs due to significant fuel savings, which could encourage sales. Which of these effects dominates for potential vehicle buyers when they are considering a purchase will determine the effect on sales. Assessing the net effect of these two competing effects is highly uncertain, as it rests on how consumers value fuel savings at the time of purchase and the extent to which manufacturers and dealers reflect technology costs in the purchase price.[30] The empirical literature does not provide clear evidence on how much of the value of fuel savings consumers consider at the time of purchase. It also generally does not speak to the efficiency of manufacturing and dealer pricing decisions, as discussed in Section B.1.2. of the Proposed Determination Appendix. Thus, we do not provide quantified estimates of potential sales impacts.

4.2.2 Evaluations of the Vehicles Subject to the Standards by Professional Auto Reviewers

The Draft TAR (Chapter 6.4.1.2) discussed initial results of an examination of the potential existence of "hidden costs"--undesirable adverse effects of GHG-reducing technologies--via a content analysis of auto reviews of MY2014 vehicles. Section B.1.5.1.2 of the Appendix for this Proposed Determination provides a high-level overview of those results, plus new results from MY2015 vehicles. Here we provide more detail on the analysis and these results.[31]

For MY2015 auto review data, RTI used the same sampling and coding procedures as for MY2014 data.[32] One new website, cars.com, was added in MY2015, because its web viewership met our criteria for inclusion. We followed the same data cleaning process as Helfand et al. (2016) and dropped the reviews of certain Volkswagen and Audi diesel vehicles due to the announcement of emissions violation in September 2015. Table 4.2 reports the number of reviews by website in our analysis for MY2014, MY2015, and the combined data. Table 4.3 reports the number of reviews by vehicle make. Reviews are themselves not conducted to reflect sales. For instance, MY2015 data contain more reviews of Audi (53) than Honda (30) vehicles. On the other hand, as with MY2014 data, the reviews by manufacturer are approximately the same as the number of models offered by manufacturer. It is possible that auto reviews focus on models with significant redesign. If so, the population of reviews is likely to have a higher proportion of new technologies than the auto population. The result of our analysis may overstate negative impacts of fuel-saving technologies if the sample includes more technologies where any kinks are not yet fully resolved.

Table 4.2 Auto Review Count by Website

Website	MY2015		MY2014		Combined	
	Review count	%	Review count	%	Review count	%
automobilemag.com	138	11.17	144	14.29	282	12.60
autotrader.com	336	27.21	224	22.32	560	25.02
caranddriver.com	202	16.36	216	21.63	418	18.68
cars.com	90	7.29	0	0	90	4.02
consumerreports.org	79	6.40	86	8.73	165	7.37
edmunds.com	105	8.50	112	11.11	217	9.70
motortrend.com	285	23.08	221	21.92	506	22.61
Total	1,235	100.00	1,003	100.00	2,238	100.00

Table 4.3 Auto Review Count by Make

Make	MY2015	MY2014	Combined	Make	MY2015	MY2014	Combined
Acura	22	24	46	Land Rover	17	15	32
Audi	53	37	90	Lexus	54	23	77
BMW	77	69	146	Lincoln	22	6	28
Bentley	16	11	27	Mini	9	11	20
Buick	11	27	38	Maserati	1	0	1
Cadillac	21	36	57	Mazda	15	49	64
Chevrolet	101	85	186	Mercedes-Benz	84	74	158
Chrysler	28	4	32	Mitsubishi	10	17	27
Dodge	41	24	65	Nissan	54	40	94
Ferrari	0	7	7	Porsche	47	34	81
Fiat	4	8	12	Ram	8	7	15
Ford	79	47	126	Rolls Royce	4	9	13
GMC	21	17	38	Scion	8	4	12
Honda	30	34	64	Smart	0	1	1
Hyundai	64	19	83	Subaru	59	25	84
Infiniti	23	25	48	Tesla	4	0	4
Jaguar	22	28	50	Toyota	75	63	138
Jeep	15	42	57	Volkswagen	51	32	83
Kia	44	44	88	Volvo	36	5	41
Lamborghini	5	0	5				

In Proposed Determination Appendix Section B.1.5.1.2, we present results that, for each fuel-saving technology, positive evaluations outweigh negative evaluations for both MY2014 and MY2015 data. To demonstrate what appears to be variation in the quality of implementation of technologies, here we summarize the evaluation results by vehicle make, reported in Table 4.4. We focus on negative evaluations, because these suggest possible problems.

There is a great deal of variation in the percentage of negative evaluations of technologies, as reported in Table 4.4. For instance, in the MY2015 data, less than 10 percent of the evaluations are negative for Bentley, Mercedes-Benz, Ram, Rolls Royce, and Tesla over the technologies examined, while over 40 percent of evaluations are negative for Mitsubishi and Scion. Moreover, between MY2014 to MY2015, Fiat, Volvo, and Lincoln had the largest decreases in the percentage of negative evaluations, while Land Rover, Scion, and Jaguar had the largest increases in the percentage of negative evaluations. There are manufacturers that were consistently rated well over the two model years. Less than 15 percent of evaluations are negative for both years for Audi, Dodge, Kia, Mercedes-Benz, Porsche, Ram, and Volkswagen.

For operational characteristics, in the MY2015 data, Bentley, Mini, Porsche, Ram, Rolls Royce, Tesla, and Volkswagen had less than 15 percent of characteristics evaluated negatively, while Mitsubishi had negative evaluations of 44 percent of its codes for operational characteristics. The correlation between the percentages of negative technology reviews and negative operational characteristics reviews is 0.62 for MY2015 data, and 0.74 for the combined data. That is, automakers that are rated well on operational characteristics also tend to have positive or neutral evaluations of efficiency technologies.

Further, we show the heterogeneity in evaluation results by vehicle make for each technology in Figure 4.2 through Figure 4.22. These reveal great variation for some technologies. For instance, for start-stop technology, as shown in Figure 4.14 using the combined data, 50 percent and 36 percent of the evaluations are negative for Subaru and BMW, respectively, while Chevrolet, Ford, Honda, and Toyota have zero negative evaluations. For the continuously variable transmission, as shown in Figure 4.16 using the combined data, over 70 percent of the evaluations are negative for Mitsubishi, 46 percent are negative for Chevrolet, and 15 percent are negative for Toyota. Using the combined data, low rolling resistance tires (Figure 4.5), electronic power steering (Figure 4.6), hybrid (Figure 4.11), and plug-in hybrid (Figure 4.12) also show a relatively greater variation in the evaluation results across vehicle makes.

The heterogeneity appears much smaller for some technologies, such as full electric (Figure 4.13) and mass reduction (Figure 4.20), which have 0 to 17 percent and 0 to 8 percent of negative evaluations respectively for all the automakers reviewed (using the combined data). Turbocharging (Figure 4.7), gasoline direct injection (Figure 4.8), high speed automatic (Figure 4.15), and dual-clutch transmission (Figure 4.17) also show a relatively smaller variation in the evaluation results across vehicle makes in the combined data.

The finding that some manufacturers, including companies with a wide portfolio of vehicle offerings, appear to implement the technologies well (as evidenced by high levels of positive evaluations) implies that other automakers may be able to improve their implementation of fuel-saving technologies and reduce or eliminate any potential hidden costs.

Table 4.4 Percent Negative Evaluations of Technologies and Operational Characteristics by Vehicle Make

Vehicle Make	2015		2014		Combined	
	% Negative Tech Reviews	% Negative Operational Characteristics Reviews	% Negative Tech Reviews	% Negative Operational Characteristics Reviews	% Negative Tech Reviews	% Negative Operational Characteristics Reviews
Acura	19.6	19.0	6.9	8.5	11.9	12.9
Audi	14.3	20.5	5.9	9.3	10.5	15.9
BMW	13.2	21.0	9.8	11.0	11.4	16.2
Bentley	2.7	9.9	0.0	6.1	1.8	8.5
Buick	22.7	17.2	27.3	22.3	26.0	20.8
Cadillac	15.2	20.2	9.2	12.2	11.1	15.2
Chevrolet	22.8	23.5	14.0	14.8	18.4	19.3
Chrysler	22.0	22.6	0.0	10.0	19.4	21.1
Dodge	10.7	19.7	12.5	20.6	11.6	20.1
Ferrari	-	-	9.5	10.4	9.5	10.4
Fiat	22.2	55.6	53.3	39.1	41.7	45.9
Ford	14.1	17.8	16.4	15.6	14.9	16.9
GMC	29.0	19.0	14.3	18.2	20.5	18.7
Honda	16.9	16.0	7.7	13.7	11.5	14.6
Hyundai	15.1	20.1	25.5	22.1	18.1	20.7
Infiniti	22.2	26.9	28.1	19.7	25.8	22.8
Jaguar	28.0	16.8	3.8	11.2	11.5	13.4
Jeep	19.2	17.2	26.9	25.1	25.4	23.7
Kia	11.2	29.0	13.3	15.0	12.4	21.3
Lambor-ghini	15.4	19.4	-	-	15.4	19.4
Land Rover	37.9	28.8	4.5	13.4	17.8	20.8
Lexus	30.5	29.1	26.4	21.6	29.1	26.5
Lincoln	15.3	21.8	38.5	24.4	19.4	22.2
Mini	19.0	12.9	22.7	20.0	20.9	16.3
Maserati	20.0	44.4	-	-	20.0	44.4
Mazda	26.9	19.1	8.9	13.6	12.1	14.6
Mercedes-Benz	9.5	15.2	14.1	13.9	11.8	14.6
Mitsubishi	42.3	47.4	39.1	56.3	40.3	52.9
Nissan	21.0	30.4	34.1	25.8	26.8	28.5
Porsche	11.4	9.1	10.9	12.5	11.2	10.5
Ram	9.1	11.4	11.1	6.5	10.3	8.9
Rolls Royce	0.0	9.1	0.0	4.6	0.0	5.7
Scion	43.8	28.3	16.7	36.4	36.4	32.0

Smart	-	-	0.0	0.0	0.0	0.0
Subaru	29.2	24.8	32.8	21.8	30.3	23.9
Tesla	0.0	10.3	-	-	0.0	10.3
Toyota	28.6	29.4	14.0	22.5	22.2	26.4
Volks-wagen	11.9	12.0	13.2	15.4	12.4	13.5
Volvo	12.6	20.2	40.0	30.0	13.8	21.1

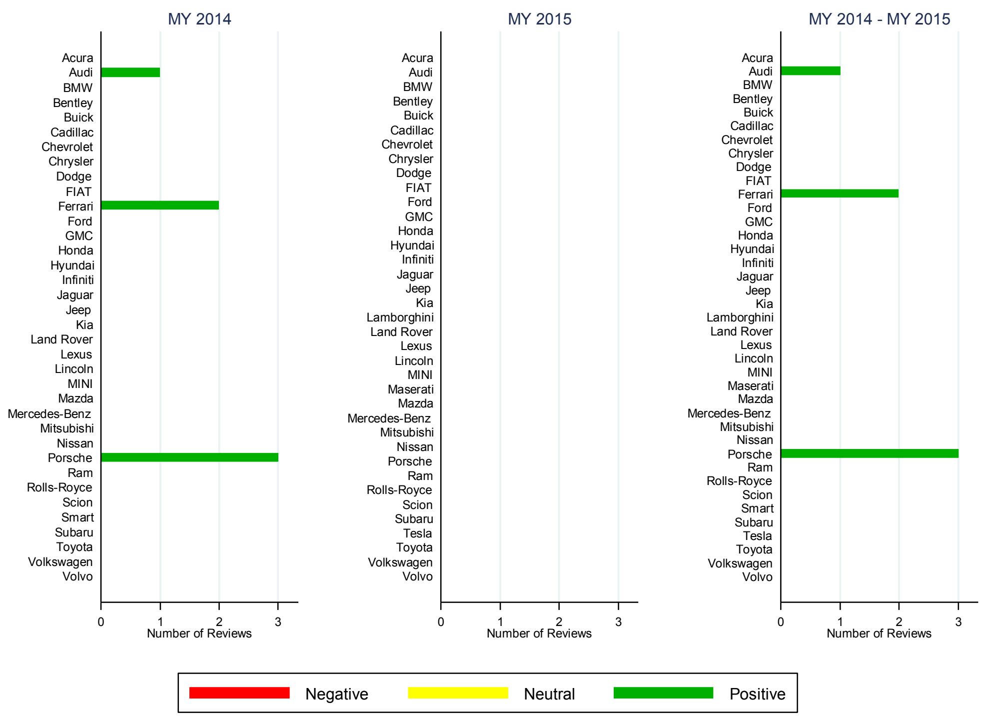


Figure 4.2 Reviews of Active Air Dam by Vehicle Make

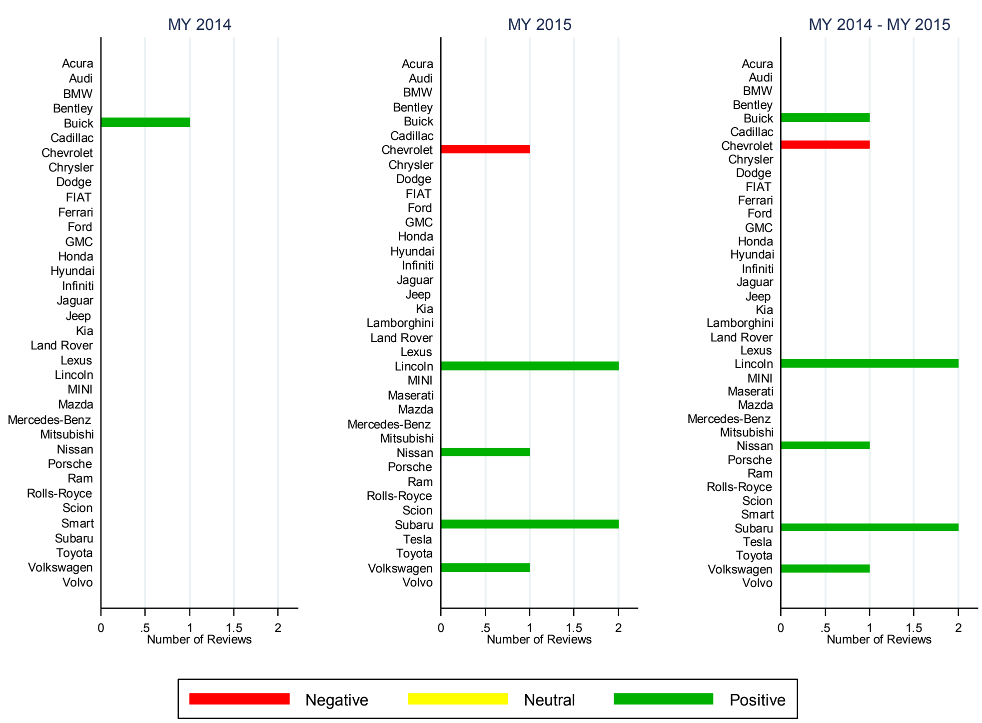


Figure 4.3 Reviews of Active Grill Shutters by Vehicle Make

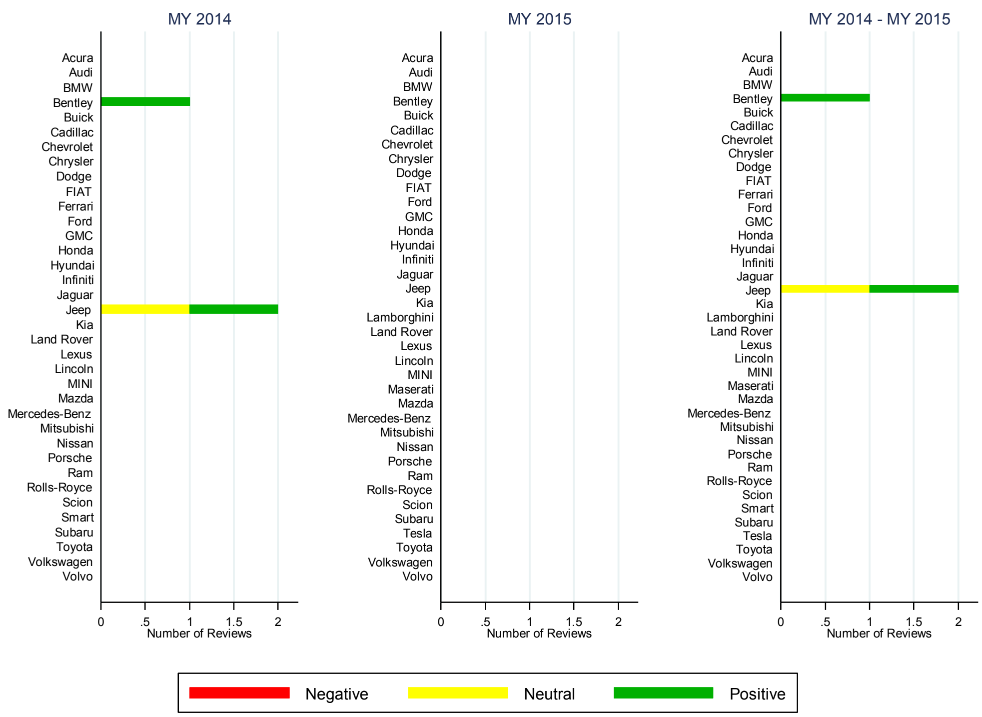


Figure 4.4 Reviews of Active Ride Height by Vehicle Make

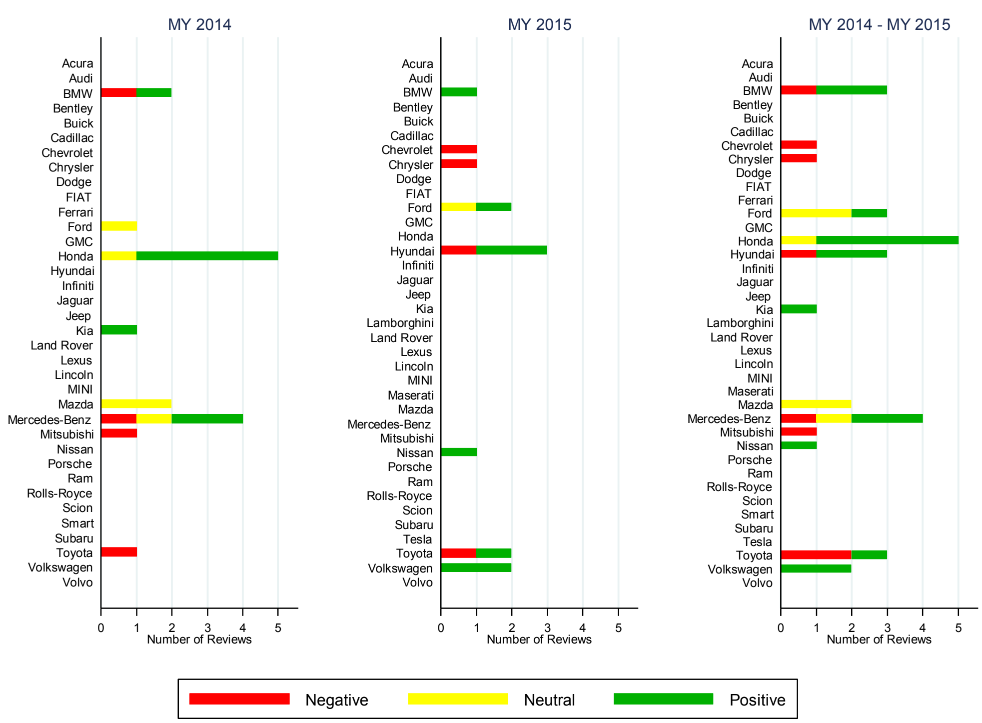


Figure 4.5 Reviews of Low Rolling Resistance Tires by Vehicle Make

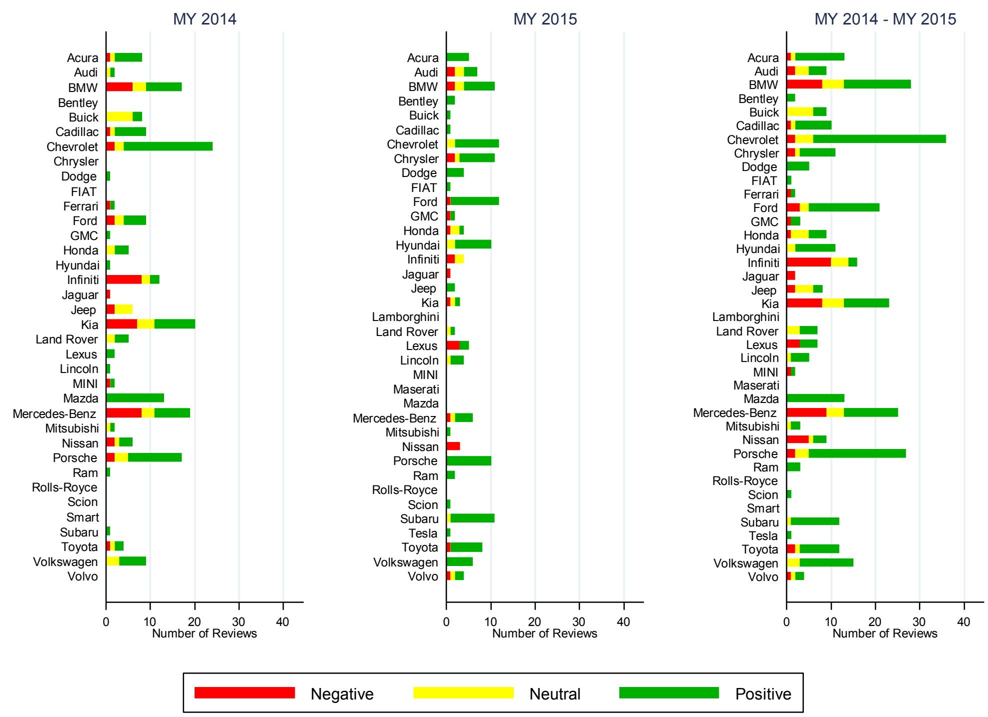


Figure 4.6 Reviews of Electronic Power Steering by Vehicle Make

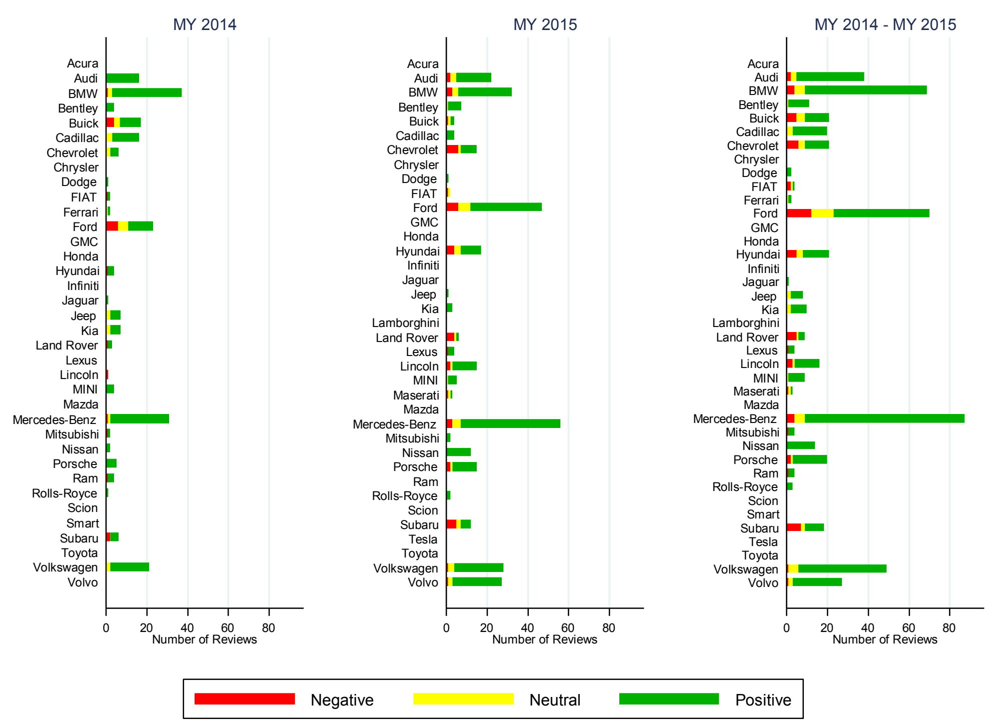


Figure 4.7 Reviews of Turbocharged by Vehicle Make

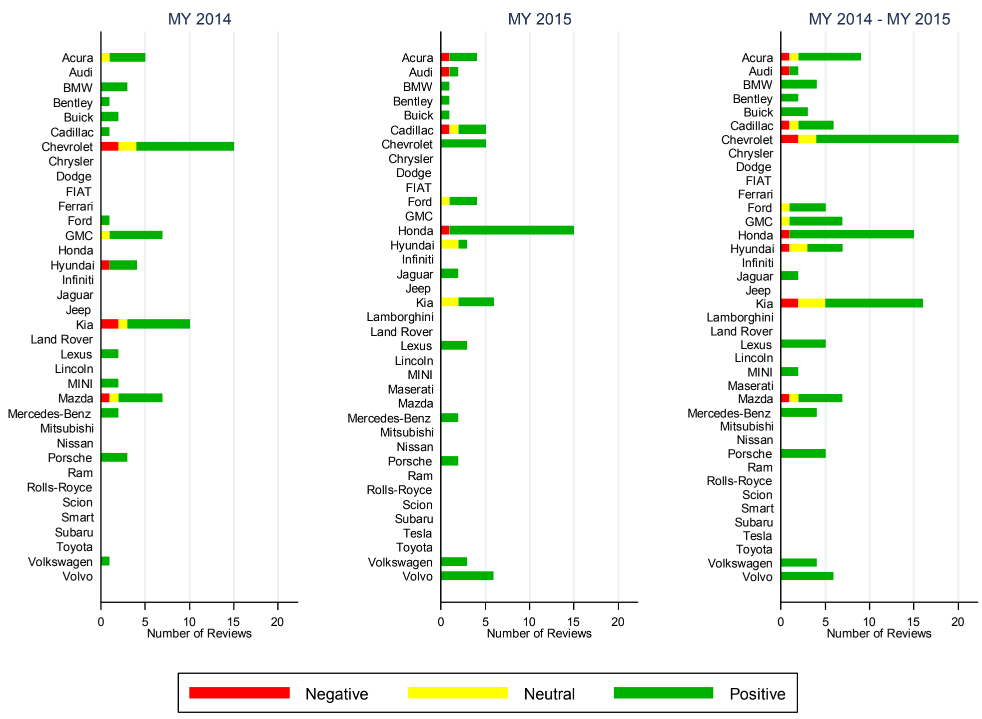


Figure 4.8 Reviews of Gasoline Direct Injection by Vehicle Make

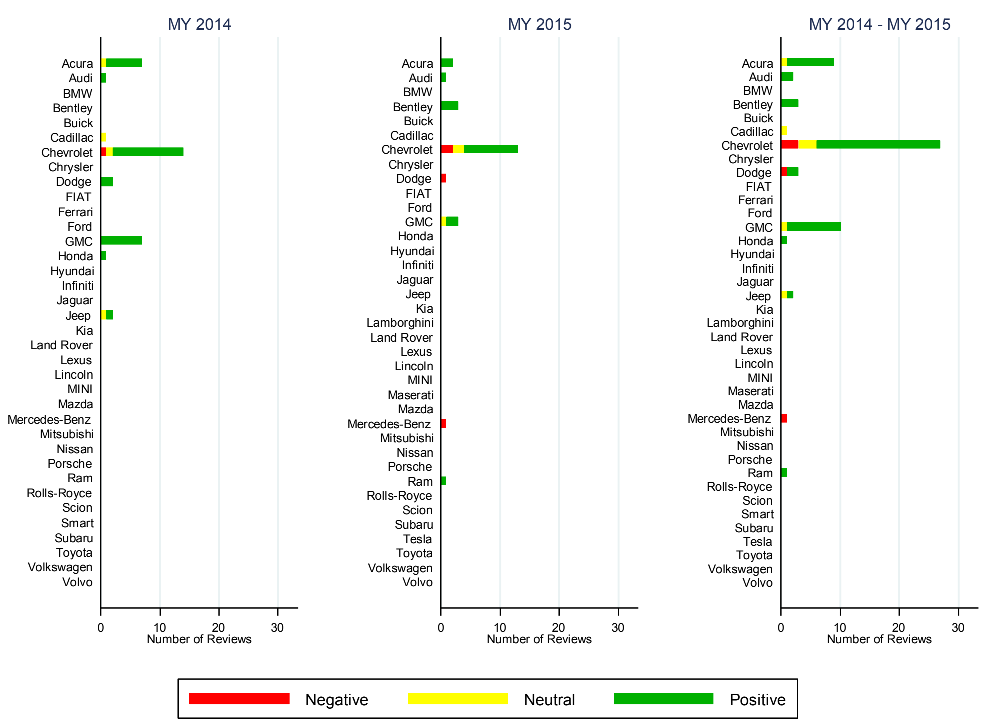


Figure 4.9 Reviews of Cylinder Deactivation by Vehicle Make

Figure 4.10 Reviews of Diesel by Vehicle Make

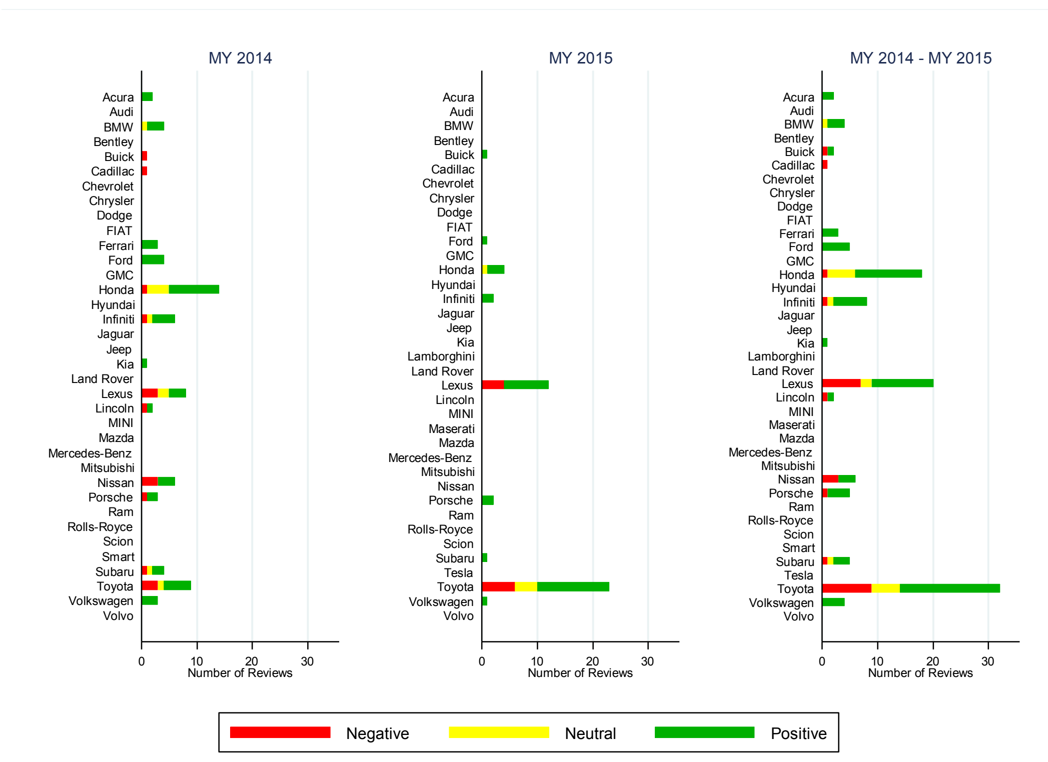


Figure 4.11 Reviews of Hybrid by Vehicle Make

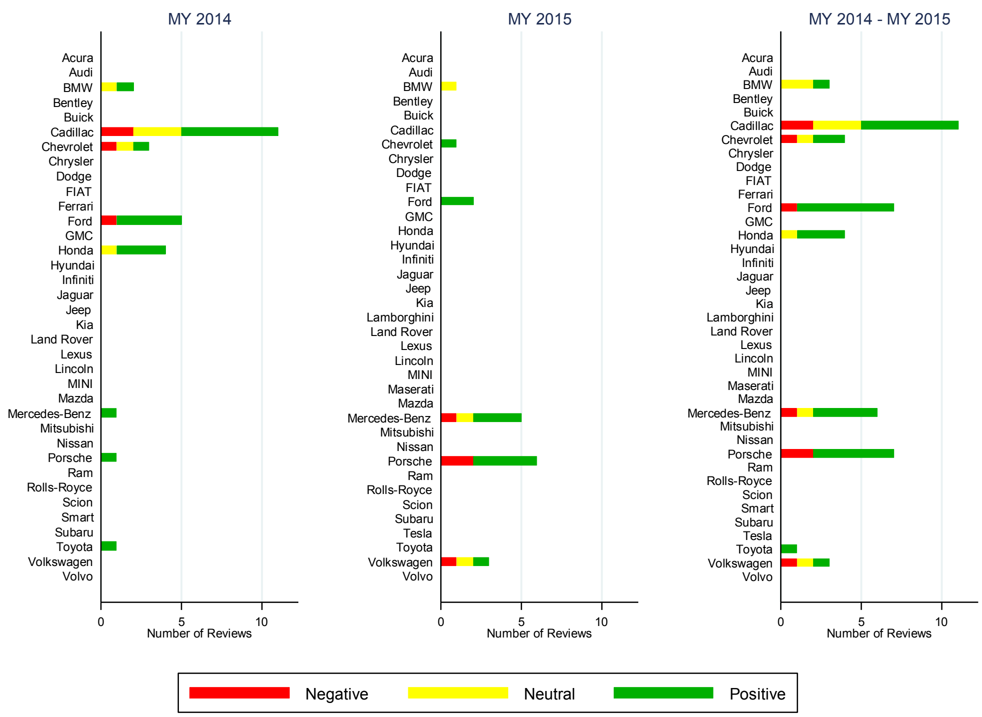


Figure 4.12 Reviews of Plug-In Hybrid Electric by Vehicle Make

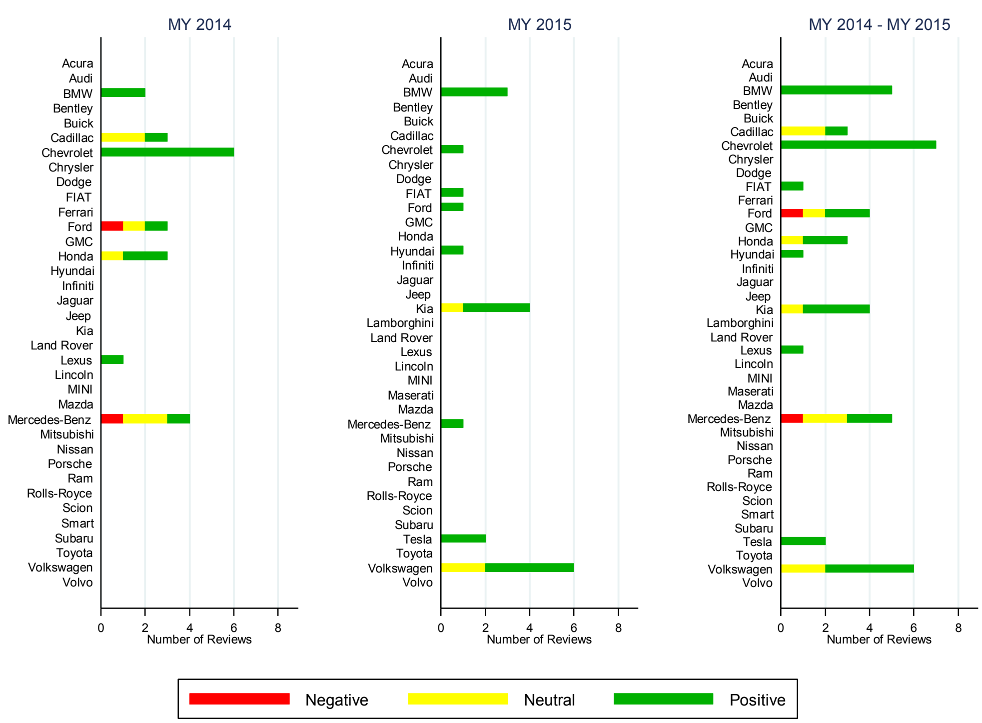


Figure 4.13 Reviews of Full Electric by Vehicle Make

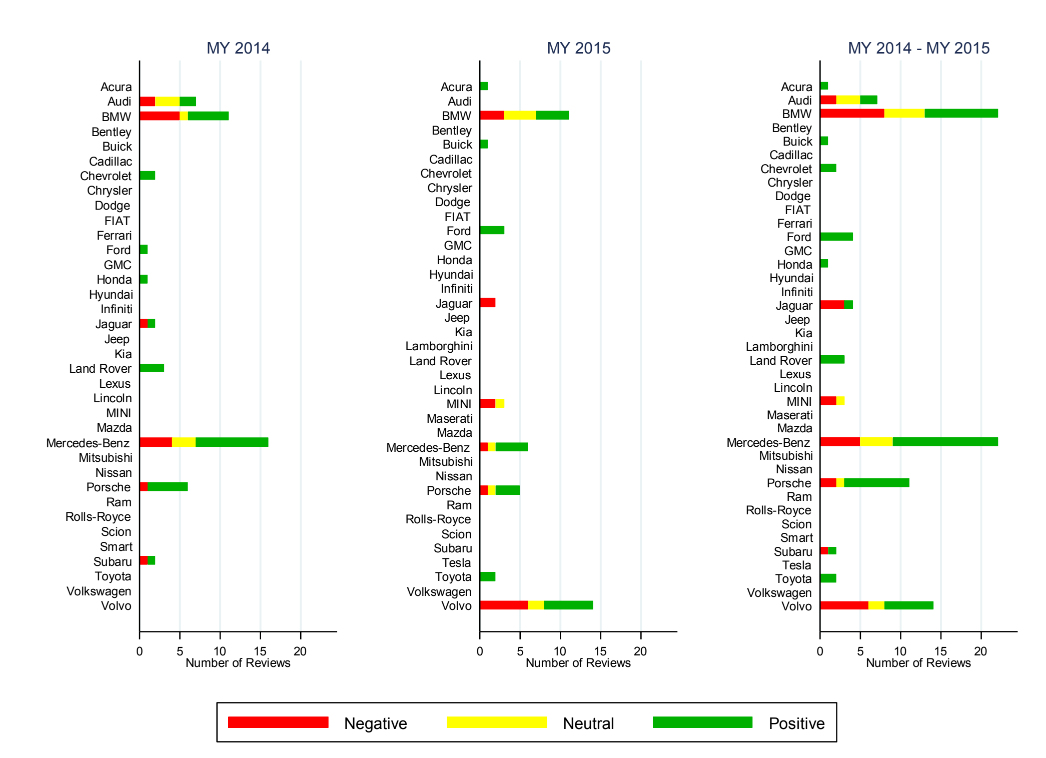


Figure 4.14 Reviews of Stop-Start by Vehicle Make

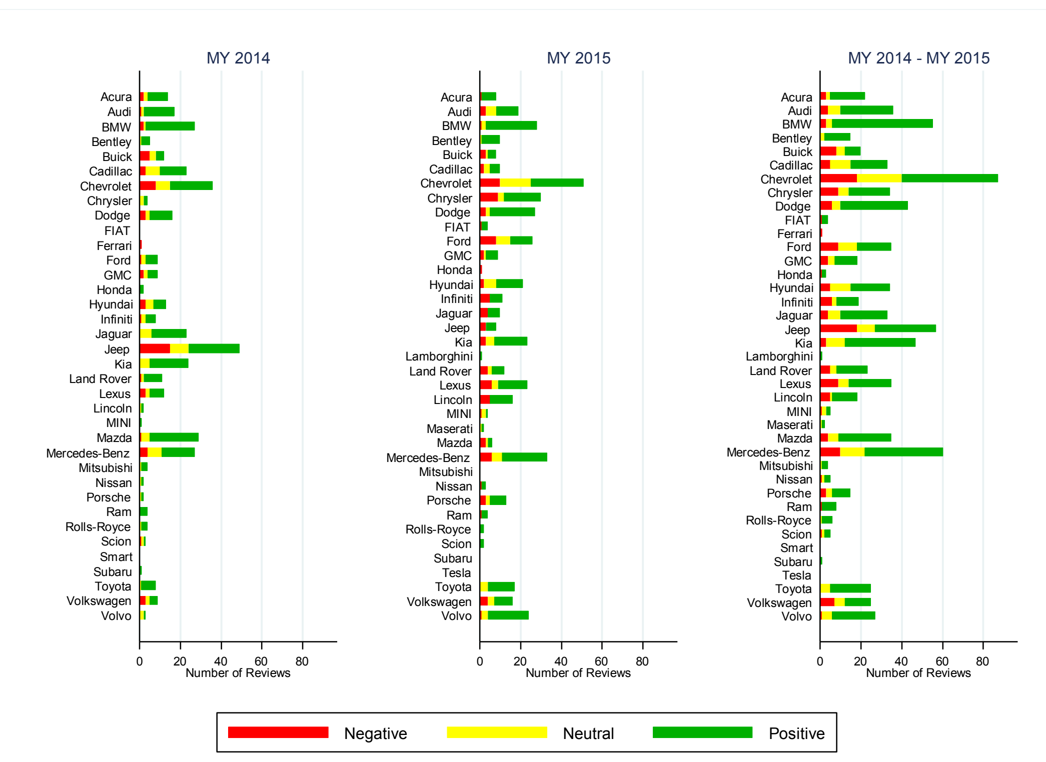


Figure 4.15 Reviews of High Speed Automatic by Vehicle Make

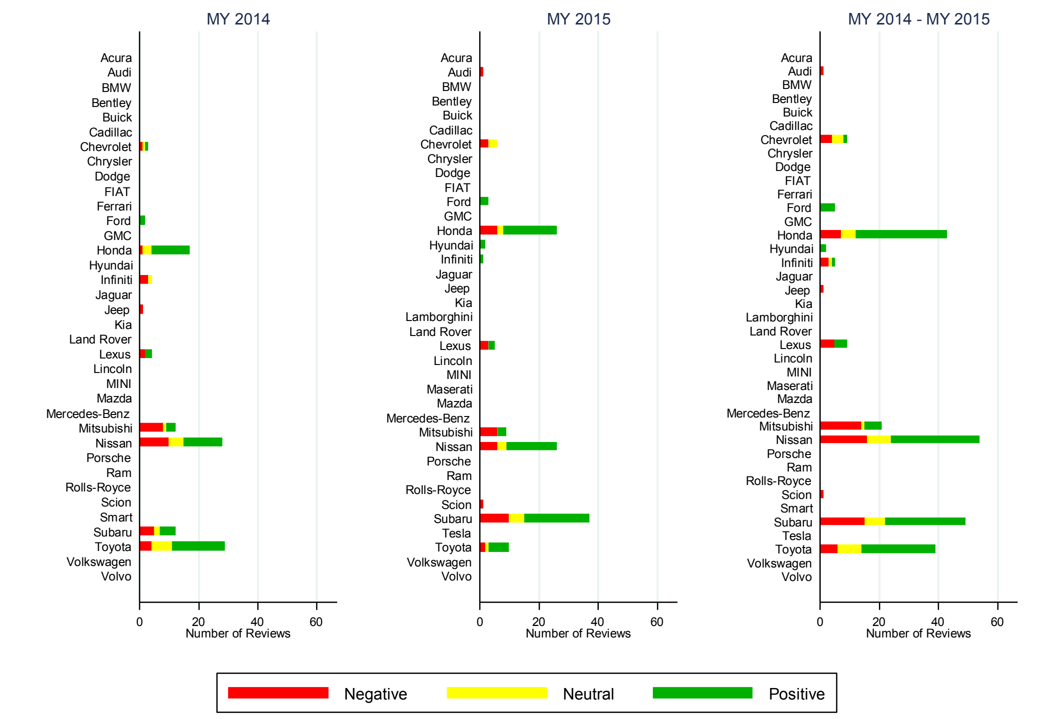


Figure 4.16 Reviews of Continuously Variable Transmission by Vehicle Make

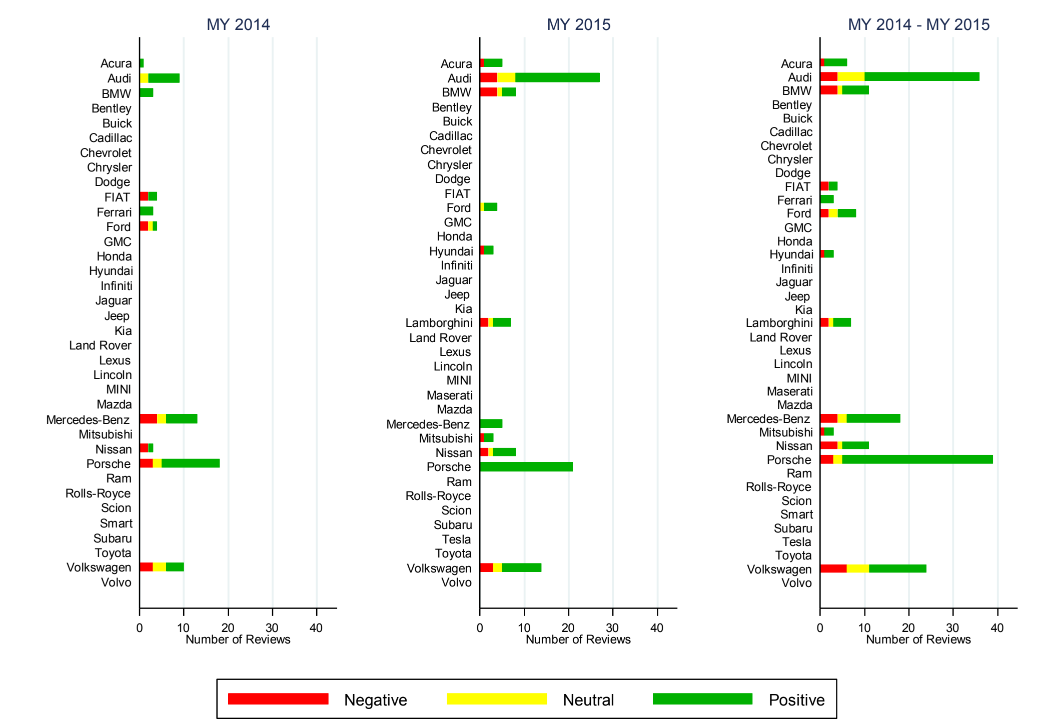


Figure 4.17 Reviews of Dual-Clutch Transmission by Vehicle Make

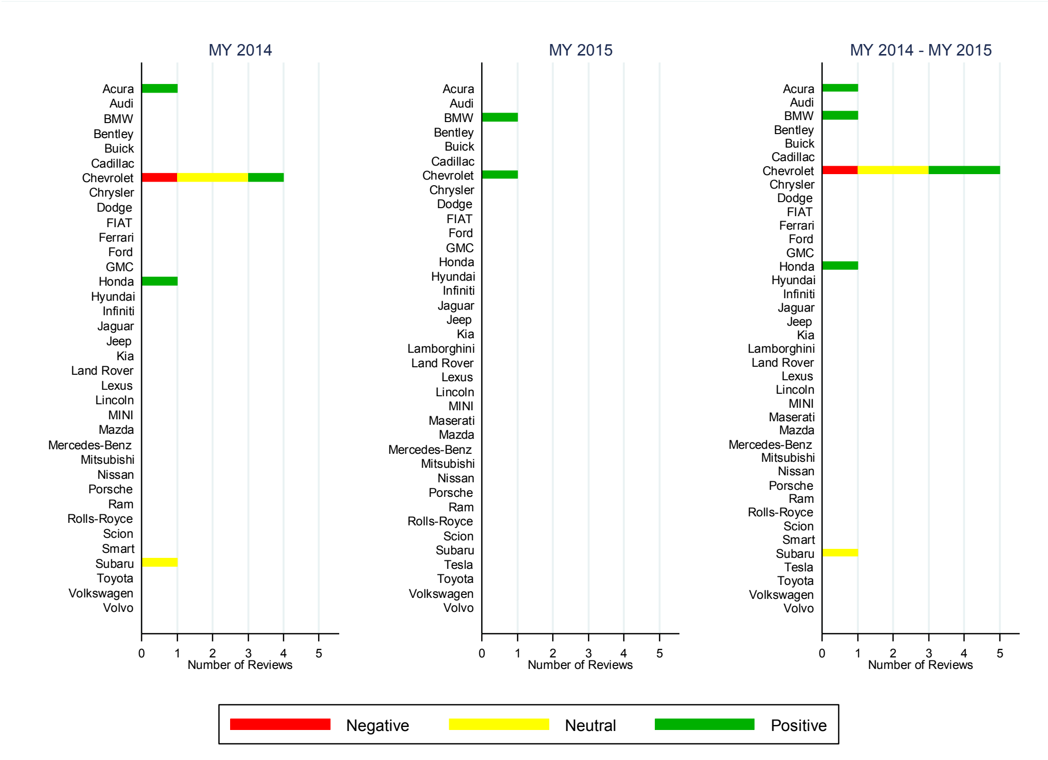


Figure 4.18 Reviews of Electric Assist or Low Drag Brakes by Vehicle Make

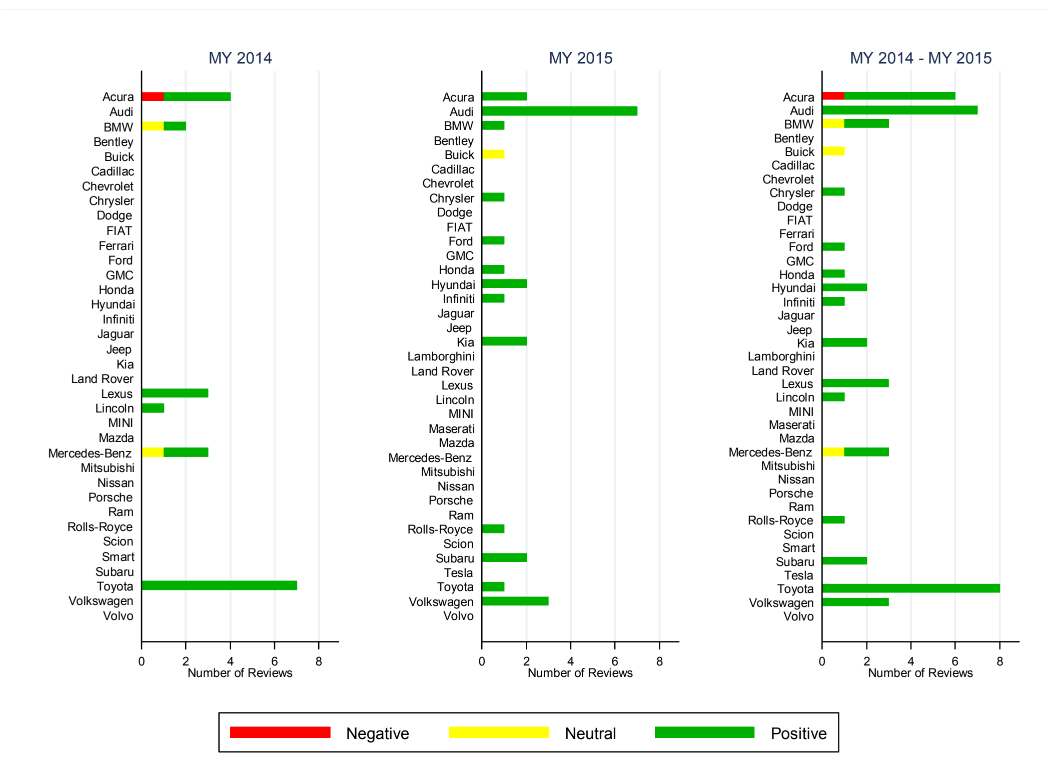


Figure 4.19 Reviews of Lighting-LED by Vehicle Make

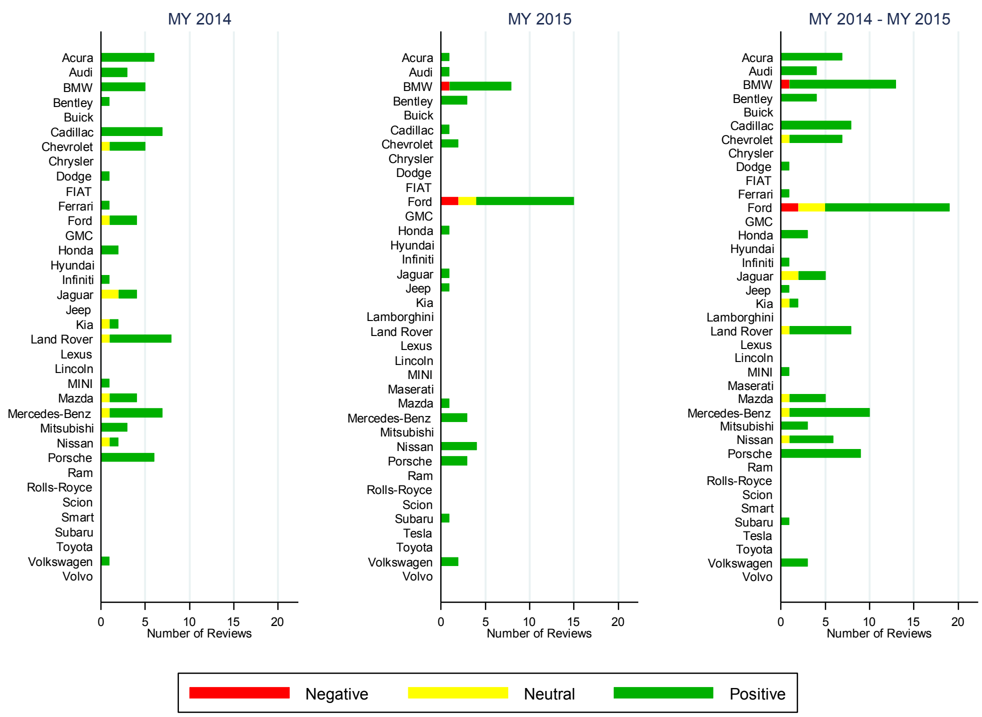


Figure 4.20 Reviews of Mass Reduction by Vehicle Make

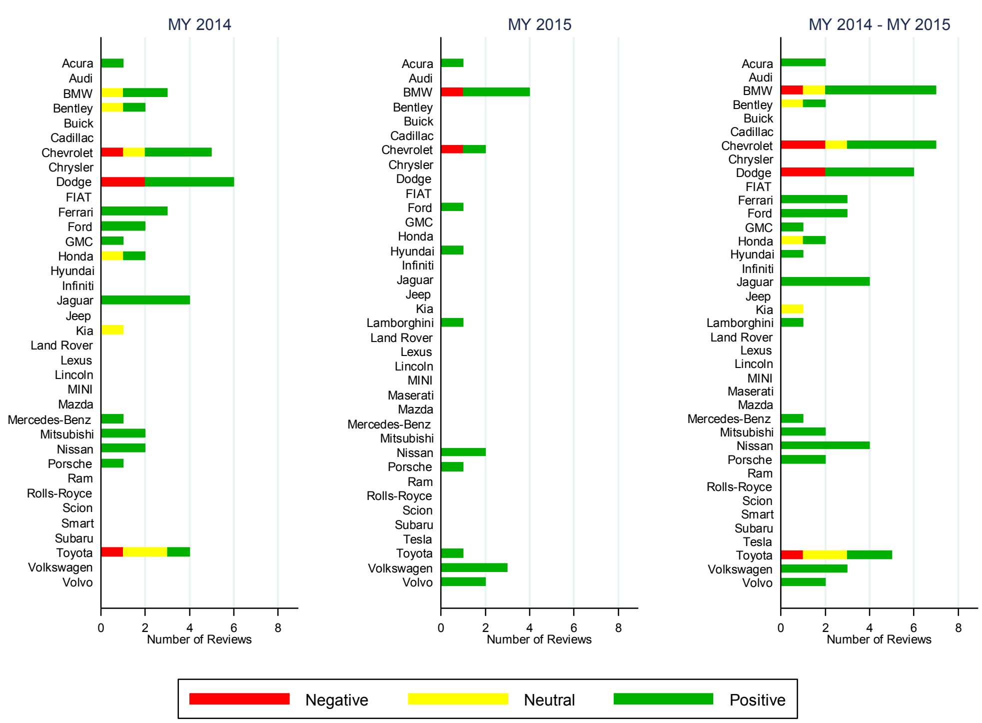


Figure 4.21 Reviews of Passive Aerodynamics by Vehicle Make

Figure 4.22 Reviews of Fuel Cell by Vehicle Make

For further assessment of the existence of hidden costs, we examine the relationship between the operational characteristics and the fuel-saving technologies using regression models. Although the data suggest that automakers that are rated well on operational characteristics also tend to implement efficiency technologies positively, there might exist selection bias that results in the correlation. For example, it could be that the same vehicles without start-stop would also generate negative evaluations of operational characteristics. To reduce the concerns about selection bias, following Helfand et al. (2016), we estimate a series of linear probability models for each operational characteristic that includes fixed effects for make, vehicle class, and website. We do this analysis separately for MY2014 and MY2015 data. In addition, we run the analysis for combined MY2014 and 2015 data, where we control for year (e.g., macroeconomic conditions common to all manufacturers), year-by-website (e.g., a website's year-specific review standards and preferences), year-by-class (e.g., year-specific innovation for a vehicle class common to all manufacturers), and year-by-make (e.g., a company's year-specific innovation and/or production strategy) fixed effects. All of those might be correlated with the review results of technology and the review results of operational characteristics, and thus bias the actual relationship.

Table 4.5 reports the number of statistically significant associations with an operational characteristic for each technology, out of 22 operational characteristics. The dependent variable across the columns is an indicator variable equal to one when a negative evaluation of the operational characteristic was recorded. Overall, the use of fuel-saving technologies is not correlated very often with a negative evaluation of an operational characteristic; indeed, the 75 negative coefficients (indicating that the technology is associated with a reduced probability of a negative evaluation of an operational characteristic) is much larger than the 24 positive coefficients (indicating that the technology is associated with an increased probability of a negative evaluation of a characteristic). The presence of GDI, passive aerodynamics, or start-stop, for instance, is not correlated in any of these data series with a negative evaluation of an operational characteristic.

Comparing the number of positive coefficients (potential hidden costs) with negative coefficients (potential hidden benefits) involves some limitations. First, counting coefficients does not indicate the magnitude of the effects. Secondly, for some of the technologies (especially active air dam, active grill shutters, active ride height, and fuel cell), statistically significant correlations may not appear because sample sizes are so small. Third, as discussed in Helfand et al. (2016), statistically significant coefficients do not indicate that the presence of the technology caused either a hidden cost or a hidden benefit; it is possible, e.g., that a characteristic in a vehicle would have been rated badly even if a different technology had been used. Nevertheless, these results indicate that hidden costs are not inevitable in the presence of these technologies. Indeed, the evidence is suggestive of some hidden benefits, as discussed in Chapter 4.1.4.

Table 4.5 Summary of Statistically Significant Regression Coefficients by Technology

Fuel-Saving Technology	MY2014: Count of Significant Positive Coefficients	MY2014: Count of Significant Negative Coefficients	MY2015: Count of Significant Positive Coefficients	MY2015: Count of Significant Negative Coefficients	Combined: Count of Significant Positive Coefficients	Combined: Count of Significant Negative Coefficients
Active Air Dam	0	1	0	0	0	1
Active Grill Shutters	1	5	0	9	0	9
Active Ride Height	0	4	0	0	0	4
Low Resistance Tires	1	1	0	7	0	3
Electronic Power Steering	1	1	0	3	3	1
Turbocharged	0	3	4	2	3	3
GDI	0	4	0	2	0	3
Cylinder Deactivation	1	3	2	2	1	5
Diesel	0	5	2	4	2	3
Hybrid	1	3	0	2	1	4
Plug-In Hybrid Electric	1	2	2	2	3	1
Full Electric	0	1	0	4	0	2
Start-Stop	0	3	0	7	0	6
High Speed Automatic	0	7	1	6	0	6
CVT	7	1	3	1	5	1
DCT	0	1	2	1	3	1
Elec Assist or Low Drag Brakes	0	2	0	9	0	4
Lighting-LED	2	5	0	2	1	3
Mass Reduction	0	4	2	3	1	4
Passive Aero-dynamics	0	6	0	7	0	5
Fuel Cell	0	0	1	6	1	6
Total	15	62	19	79	24	75

4.3 Impacts of the Standards on Vehicle Affordability

Section B.1.6 of the Proposed Determination Appendix provides an overview of the analysis of the impacts of the standards on vehicle affordability. As will be discussed below, affordability is not a well-defined concept, but it is potentially an important consideration not only to policy-makers, but to all stakeholders.

This TSD subchapter expands upon the analysis in the Appendix, and updates information presented in the Draft TAR, as well as in a memo to the docket on affordability.[33] It begins with a literature review on the conceptualization and definition(s) of affordability for various consumer goods. It then poses, and subsequently assesses, four questions by which to analyze vehicle affordability:

- Effects on lower-income households;
- Effects on the used vehicle market;
- Effects on access to credit; and,
- Effects on the low-priced vehicle segment of the new vehicle market.

4.3.1 Literature Review: Definitions of Affordability

While the term “affordability” is very commonly used in colloquial settings, there is little consensus on an academic definition for the term, and the concept of “affordability” is murky at best. Hancock (1993) lamented that “affordability has been gaining much currency in housing policy debates, but neither government nor academic researchers have given much consideration to defining it.”[34] Quigley and Raphael (2004) stated that “economists are wary, even uncomfortable, with the rhetoric of ‘affordability,’ which jumbles together in a single term a number of disparate issues…”[35] Bradley (2008) identified affordability as “a vague concept…When pundits use the word ’afford,’ there is no clear definition of affordability; it is at best a subjective notion.”[36] Perhaps most candidly, Bartl (2010) declared that “affordability is a new ‘alien’ concept penetrating the field of contract and consumer law.”[37]

Even though the concept of affordability has been characterized as vague, subjective, alien, and vexed, several economists and federal agencies have attempted to define affordability, most often in the context of specific goods. These goods include energy, food, telephone service, health insurance, and housing.

For energy, Bartl (2010) defines affordability as “primarily an economic category having to do with the ability of certain consumers or consumer groups to pay for a minimum level of service.” She states that affordability has two dimensions: “First, it is necessary to ensure reasonable prices for all users, and, secondly, to ensure the provision of services to persons who cannot afford it under normal market (or prior monopoly) conditions.” This assumes that universal access to energy services is a basic necessity. Fankhauser and Tepic (2007), for water and energy, have a similar definition, and then operationalize it as the share of monthly expenditures (or income) spent on utility services.[38]

For food, Blaylock et al. (1999) determined affordability based on the ratio of expenditures on food to household income.[39] However, Blaylock et al. also explained that food expenditures are not dictated entirely by household income and costs: nutritional value, taste, and convenience factored into consumers' preferences on food choices. Furthermore, they argued that the costs of food consumption must be considered in a short-term context, including the upfront cost of food purchases, the time expended purchasing food, and sacrifices in taste for lower upfront cost or nutritional quality; and a long-term context, including the potential health risks of eating cheap, nutritionally questionable food. For example, a reduction in public consumption of high-cholesterol foods after increasing public information on the risks of cholesterol showed that "it is not inevitable that affordable food will defeat nutrition information in determining diets." Although "affordable" here is defined as having low upfront cost, consumers appear to factor in long-term costs, such as health risks, when deciding whether food is affordable.

The Department of Health and Human Services also uses the ratio-of-income approach to determine food affordability for federal poverty guidelines. The Department of Agriculture determines a nutritionally adequate bundle of food for households, and the Department of Health and Human Services sets the poverty standard "based on the relationship of the price of this bundle to income" (Glied, 2009).[40] This definition of affordability thus takes both upfront cost and a measure of food quality into account.

For telephone service, Milne (2000) uses a similar ratio approach to determine affordability. She states that one key assumption is that "there is a certain percent of household income which, on average, a new subscriber finds acceptable to devote to telephone service," referring to this as the "affordability threshold."[41] However, she also states that the assumption that all households with incomes beyond the affordability threshold will subscribe to telephone service "does not describe individual behavior." She explains that "households will deviate from this behavior in both directions," but that "we can be confident that propensity to subscribe to the phone does increase with income level, and decrease with proportion of expenditure devoted to telecoms." Thus, this definition of affordability rests primarily on the share of income devoted to telephone expenditures, but gives some acknowledgment to the effect of consumer preferences. Additionally, Milne essentially defines access to telephone service as a necessity, declaring that "the notion that basic telephone service should be affordable has received widespread assent."

For health insurance, Glied (2009) distinguishes between colloquial and more academic usages of affordability. The more colloquial usage "implies that the primary reason someone chooses not to purchase a good or service is that the person does not have the ability to pay for it." However, in more academic terms, "a household is said to afford such a purchase if it would be left with enough income to meet its other socially defined minimum needs." Like food, energy, and telephone service, health insurance in this context is presumed to be a necessity, for which there is a socially defined minimum level of necessary consumption.

In discussions of affordability, perhaps the most commonly considered good is housing. Maclennan and Williams (1990, cited in Haffner and Heylen 2011, p. 595) define affordability as "concerned with securing some given standard of housing (or different standards) at a price or a rent which does not impose, in the eyes of some third party (usually government) an unreasonable burden on household incomes."[42] Again, this definition refers to socially defined minimum standards for housing and other goods. Similarly, Bramley (1990) characterizes affordability as a situation where "households should be able to occupy housing that meets well-established (social sector) norms of adequacy (given household type and size) at a net rent which leaves them enough income to live on without falling below some poverty standard."[43]

Clarifying this definition somewhat, Whitehead (1991) refers to affordability as "the opportunity cost of housing vis-à-vis other goods and services."[44] Hancock (1993) refers to the essence of the concept of affordability as "what has to be foregone in order to obtain the merit good and whether that which is foregone is reasonable or excessive in some sense."[45] Also taking opportunity cost into account, Stone (2006) defines affordability as expressing "the challenge each household faces in balancing the cost of its actual or potential housing, on the one hand, and its non-housing expenditures, on the other, within the constraints of income."[46]

As with other goods, housing affordability is often operationalized using a ratio approach. The Department of Housing and Urban Development (HUD) (U.S. Department of Housing and Urban Development, 2015) characterizes a household as able to afford housing if it pays no more than 30 percent of its income on housing.[47] HUD also considers supply in its metrics to analyze housing affordability. In its "Worst Case Housing Needs" biennial report to Congress (U.S. Department of Housing and Urban Development, 2011), HUD highlights the supply of rental units that would be affordable (presumably using the 30 percent-of-income standard) to consumers within a given income class (Steffen et al., 2015).[48]

While ultimately disagreeing with the simple use of the ratio approach to determine housing affordability, Bogdon and Can (1997) also incorporate supply into their definition of housing affordability by using the housing affordability mismatch approach, which "considers both housing supply and housing demand by comparing the existing housing cost distribution with the distribution of household incomes."[49] Similarly, Gan and Hill (2009) develop affordability indices that take account of "the whole distribution of household income and house prices rather than just the median."[50] This accounts for the demand for various housing types based on household income and the supply of housing units appropriate for households with various incomes. Fisher et al. (2009) expand on the supply concept by advocating tracking the supply of units in different geographic areas and accounting for the effect of the spatial distribution of various housing units on prices.[51]

As described briefly above, despite its widespread use in affordability indices for a variety of goods, the ratio approach is also widely criticized. Hancock (1993) states that "a ratio definition says nothing about what might be an acceptable opportunity cost of that which is being consumed," and that it "therefore makes little sense to define affordability in terms of the ratio of housing costs to incomes if it is believed that opportunity cost is important." Stone (2006) echoes this criticism, explaining that the ratio approach assumes that someone with a lower income who spends as high a proportion of his/her income on housing as someone with a higher income can afford to spend much less in an absolute sense on other necessities. Bogdon and Can (1997) also criticize the ratio approach as "flawed." They state that the ratio approach does not account for quality, differences in preferences, households' actual financial constraints, or actual user costs. Instead, Stone (2006) advocates the use of the residual income approach, which measures the actual amount of disposable income (as opposed to the percentage of income) remaining after accounting for housing expenditures and determining whether that residual income is sufficient to purchase minimum acceptable quantities of other necessities.

Another trend within more recent housing affordability literature is distinguishing between short-term affordability and long-term affordability. Haffner and Heylen (2011) define the short-term costs as the "out-of-pocket cash flows or expenses that households make to finance the access to their home," and the long-term affordability as the "'long-run ability' of households to pay the so-called user costs or price of housing consumption." This relates closely to Gan and Hill's (2009) distinction of purchase versus repayment affordability, although repayment affordability only takes the cost of repaying the mortgage into account and does not encompass the broader user costs associated with Haffner and Heylen's long-term affordability concept.

User costs are certainly not a new idea in housing affordability literature. Hancock (1993) states that "in theory, the housing costs of owner-occupiers should be measured by the user-cost, which takes the opportunity-cost of equity, depreciation, and the effect of capital gains into account, in addition to the mortgage payments, local property taxes and the maintenance of the property." Quigley and Raphael (2004) also note user cost: "To an economist, however, the affordability of owner-occupied housing is a bit more complicated – by taxes, by depreciation and by capital gains." Similarly, Bogdon and Can (1997) recognize that "monthly home owner costs may also be a misleading measure because the true measure for home owners is the user cost, which includes expected appreciation."

Like food, much of the literature on housing affordability also emphasizes the importance of incorporating quality. Lerman and Reeder (1987) develop a "'quality-based' definition of the housing affordability problem that distinguishes households having too little income to rent minimally adequate but decent, safe, and sanitary housing for less than a specified percentage of income (30 percent) from households whose incomes are sufficient."[52] Fisher et al. (2009) clarify the usage of quality set forth by Lerman and Reeder to "develop an affordability methodology that accounts for job accessibility, school quality, and safety." Thalmann (1999) uses two indicators of housing affordability in a similar fashion: one indicator "compares income to the average rent the market charges for housing deemed appropriate for a household," and the second indicator "compares current housing consumption with appropriate housing consumption."[53] This approach takes a different tack than many — instead of identifying just the socially acceptable minimum quality of housing for a given household, Thalmann also identifies a socially acceptable maximum quality and uses this range to determine affordability of the housing stock.

Quigley and Raphael (2004) note that affordability in the context of housing "jumbles together in a single term a number of disparate issues: the distribution of housing prices, the distribution of housing quality, the distribution of income, the ability of households to borrow, public policies affecting housing markets, conditions affecting the supply of new or refurbished housing, and the choices that people make about how much housing to consume relative to other goods." And like other goods that are considered basic necessities, Quigley and Raphael refer to a "socially imposed minimum standard" for housing.

However, Quigley and Raphael state that defining affordability for housing is not the same for all incomes. For American households who own their home, "housing 'affordability' refers to the terms on which dwellings can be purchased and loans to purchase these assets can be amortized." However, for households with lower incomes, "'affordability' refers to the terms of rental contracts and the relationship between these rents and their low incomes." Stone (2006) shares this sentiment: "Affordability is not a characteristic of housing – it is a relationship between housing and people. For some people, all housing is affordable, no matter how expensive it is; for others, no housing is affordable unless it is free." This implies that how one defines affordability can depend heavily on income.

Despite differing definitions of affordability offered for different types of goods, there are many similarities and shared themes across definitions. One shared theme is that instead of focusing on the traditional economic concept of willingness to pay, any consideration of affordability must also consider the ability to pay for a socially defined minimum level of a good. As discussed below, however, all of the goods considered in this literature review were considered basic necessities, and the absence of a socially defined minimum level of adequate consumption of the good in question complicates determining consumers' ability to pay for such a good.

Often, the ability to pay is determined based on the proportion of income devoted to expenditures on a particular good. However, this ratio approach is widely criticized. For example, it does not account for the opportunity cost associated with the consumption of a particular good. That is, when purchasing at least the socially-defined minimum level of one good, one must consider the utility of other goods, some of which may be necessities, which a consumer must forego based on his/her income. The ratio approach also does not incorporate quality differences in the considered good. For instance, one consumer may pay $700 per month to rent a spacious, clean, well-maintained apartment while another consumer with the same income may pay $700 per month to rent a small, moldy, crumbling apartment that does not meet socially defined minimum housing standards. The ratio approach also does not incorporate heterogeneity of consumer preferences. For instance, two consumers with the same income may purchase housing of wildly different quantity and quality based on the utility they receive from housing versus other goods that they can purchase.

Considering this heterogeneity of preferences is important for attempting to identify the socially defined minimum level of service necessary for each type of good. Here, there are two approaches at play. One is the normative approach, which uses a set and arbitrary level of service as the minimum adequate level for consideration of the ability to pay. The other is the behavioral approach, which expands on the normative approach by considering consumer preference intensity and determining whether the consumer of a particular income with the median preference intensity can purchase the normatively-determined minimum acceptable level of service.

One alternative approach to determining the ability of consumers to pay for a certain good is the permanent income hypothesis, which states that consumers' levels of consumption are explained more by what those consumers expect to earn over a period of time rather than their temporary income, which can often fluctuate wildly. Thakuriah and Liao (2006) thus use total expenditures as a proxy for consumers' permanent income in order to estimate consumers' ability to pay for transportation expenditures.[54]

Another common theme, particularly when discussing affordability of housing, is considering both the short-term costs and long-term costs associated with consumption of a particular good to assess affordability. This includes both the cost of accessing the good, which often refers to access to and cost of financing, as well as the user cost of the good over time. These costs are not equal. For instance, one may be able to afford the costs associated with owning a home, including mortgage repayment, property taxes, maintenance, and depreciation, while not having sufficient savings to cover the necessary down payment to access financing.

4.3.2 Relating Affordability Themes to Vehicle Standards

All the goods considered in this literature review (energy, nutrition, basic telephone service, health insurance, and housing) arguably could be considered necessities. For instance, with health care, Bundorf and Pauly (2009) "assume that there is a 'special' societal interest in medical insurance and medical care that need not apply equally to other types of consumption."[55] These goods thus have socially defined minimum adequate levels of consumption (although there may not be consensus on those levels).

However, unlike the goods discussed above, there is no socially defined minimum level of consumption for vehicles. Considering consumption only of vehicles defines the service provided by vehicles too narrowly. Vehicles are one means to the end of transportation.

A thorough review revealed no attempts to define the affordability of transportation, and vehicles more specifically. Thakuriah and Liao (2006) attempt to define ability to pay for transportation expenditures, but do not offer a definition of affordable transportation. A report by the Manhattan Strategy Group for the Department of Transportation and the Department of Housing and Urban Development (HUD) (Schanzenbach and McGranahan, 2012) attempts to create metrics of various types of vehicle costs to be included in HUD's Location Affordability Index, which considers housing and transportation costs based on location. However, this report also did not attempt to define vehicle affordability.[56]

Given the prevalence of heavily subsidized public transit systems, including free rides for vulnerable populations, it seems that societies often consider access to transportation in some sense a basic necessity. However, it is not clear how to identify the socially acceptable minimum level of transportation service. It seems reasonable to assume that such a socially acceptable minimum level should allow access to employment, education, and basic services like the grocery store, but it is not clear where consumption of transportation moves from practical to luxury. Normatively defining the minimum adequate level of transportation consumption is difficult given the heterogeneity of consumer preferences and living situations. As a result, it is challenging to define how much residual income should remain with each household after transportation expenditures. It is therefore not surprising that academic and policy literature have largely avoided attempting to define transportation affordability.

We therefore do not propose a quantitative measure of the affordability of new vehicles. As discussed in Proposed Determination Appendix Section B.1.6, although some comments we received on the effects of the standards on affordability requested a quantified analysis of the issue, those comments did not suggest methods for that analysis. Instead, as in Draft TAR Chapter 6.5, we consider four questions that relate to the effects of the LDV GHG standards on new vehicle affordability: how the standards affect low-income households; how the standards affect the used vehicle market; how the standards affect access to credit; and how the standards affect the low-priced vehicle segment.

4.3.3 EPA's Assessment of the Impacts of the Standards on Affordability

The effects of the standards on vehicle affordability are discussed in the Proposed Determination Appendix, Section B.1.6. Below we report further detail about the data and our assessment of four aspects of affordability: the effects of the standards on lower-income households, on the used vehicle market, on whether access to credit may limit consumer's ability to purchase new vehicles, and on the availability of low-priced vehicles.

4.3.3.1 Data: Consumer Expenditure Survey

To analyze the characteristics of households who purchase new and used vehicles and the vehicles that these households purchase, we used the public use microdata of the Consumer Expenditure Survey (CES), specifically the interview and detailed expenditure files for years 2007 through 2015 (Bureau of Labor Statistics, 2015).[57] The CES is performed annually by the Department of Labor–Bureau of Labor Statistics (BLS). It is conducted in-person based on a representative sample of U.S. addresses.

Data from this survey were chosen for several reasons. First, the survey includes a sample of consumer units that is designed to be representative of the total US population. The sampling frame for each CES is derived from a list of households included in the 2000 Census and a list of households constructed after the 2000 Census.[O] Consumer units are roughly equivalent to households, and from this point forward will be referred to as "households."[P] Second, the survey is performed annually, which allows us to track recent vehicle purchase behavior over a greater number of reference years than other data sets and establish trends. Third, the CES includes detailed information on both household demographics and major expenditures, particularly related to vehicles and transportation. Fourth, the public use microdata for the CES from years 2003 onwards is available online for free, which allows easy public access to the data used in our analysis.[Q] Fifth, the CES is widely used by policymakers and academics to study welfare changes across socioeconomic groups.[R]

Other articles and reports have used the CES to examine the relationship between vehicle purchases and household characteristics. For example, Goldberg (1996) used microdata from the CES to try to explain auto dealer price discrimination based both on household characteristics (e.g. race or gender) and vehicle purchase characteristics (e.g. trade-in and financing source).[58] Yurko (2011) used data from the CES to examine the relationship between household income and vehicle quality, specifically vehicle age.[59] Schanzenbach and McGranahan (2012) used estimates for the costs of car ownership obtained from CES data to include in the Department of Housing and Urban Development's Location Affordability Index. Thakuriah and Liao (2006)

[O] For more information on how the sample for the CES is selected, please see User's Documentation included in the CES public use microdata for the Interview Survey each year and the CES Frequently Asked Questions, http://www.bls.gov/cex/faq.htm#q17.

[P] According to the CES glossary (http://www.bls.gov/cex/csxgloss.htm), "A consumer unit comprises either: (1) all members of a particular household who are related by blood, marriage, adoption, or other legal arrangements; (2) a person living alone or sharing a household with others or living as a roomer in a private home or lodging house or in permanent living quarters in a hotel or motel, but who is financially independent; or (3) two or more persons living together who use their income to make joint expenditure decisions. Financial independence is determined by the three major expense categories: Housing, food, and other living expenses. To be considered financially independent, at least two of the three major expense categories have to be provided entirely, or in part, by the respondent."

[Q] To access the public use microdata for the CES, visit the Public-Use Microdata Home Page, http://www.bls.gov/cex/pumdhome.htm.

[R] For more information on how the CES is used by academics and policymakers, visit "Value of the Consumer Expenditure Survey," http://www.bls.gov/respondents/cex/cevalue.htm.

used microdata from the CES to compare total annual expenditures (as a proxy for permanent incomes) with investments in mobility.

Note that this analysis and the CES focus on household vehicle purchase behavior, and not the entire new or used vehicle market, which includes fleet purchases. It is also important to note that we do not consider leases in this analysis of CES data. The leased vehicle data reported in the CES do not include the calendar year when the lease was contracted; as a result, we are unable to compare household leasing behavior with vehicle purchase behavior on a calendar year basis. We thus focus only on vehicles owned by residential households and thus understate the number of vehicles in households.

One limitation with using the CES is that the data on expenditures and households' characteristics are self-reported. This makes the data subject to problems with respondents' recall of information, or misrepresentation. This is a limitation of all survey data and is not unique to the CES.

The expenditure variables in the CES we examine are CARTKNPQ and CARTKNCQ for expenditures on new cars and trucks, CARTKUPQ and CARTKUCQ for expenditures on used cars and trucks, and GASMOPQ and GASMOCQ for expenditures on gasoline and motor oil. Following the estimation procedure section from the CES documentation, we calculated an aggregated measure for a calendar year by weighting the amount of time (MO_SCOPE in the documentation) so that each reported expenditure actually applies to the year based on the interview year and interview month. We then took weighted averages of the variables, where our final weight in Stata is the product of the "MO_SCOPE" and the "finlwt21" variable, the variable recommended by the BLS for estimating the population and was used for all means and medians.[S] By this estimation procedure our calculations of expenditures on new vehicles, used vehicles, and gasoline and motor oil were able to exactly match the mean expenditures reported in the online CES tables (e.g., for 2015, see http://www.bls.gov/cex/2015/combined/quintile.pdf, "Cars and trucks, new," "Cars and trucks, used," and "Gasoline and motor oil").

The income variable we examined is total household income before tax, FINCBTXM in the CES. In the Draft TAR, we used after-tax income, FINCATAX in the CES. We switched to before-tax income because before-tax income is more typically used in analyses of the CES data. In addition, BLS had not derived the non-imputed after-tax income since 2015, and has derived a new imputed after-tax income, FINATXEM, since 2013; as a result, the data series is not consistent over the time period studied here. We used the estimation procedure mentioned above to obtain weighted median income for each year. Using the weighted median income (in 2015, it was $50,000), we divide the annual sample into lower-income households (those with income less than $50,000) and higher-income households (those with income over $50,000), and produce summary statistics of expenditures by the two income groups.

In order to generate debt-to-income (DTI) ratios, the debt expenditure variables we used are MRTPMTX for mortgage, MRTPMTG for home equity loans, PAYMENTX for vehicle loans, QRT3MCMX for rental home payments, and CONTEXPX for contributions, including child

[S] See http://www.bls.gov/cex/2015/csxintvw.pdf, p. 24-30, for the documentation for 2015 CES data and estimation procedures of unweighted and weighted statistics.

support and alimony only. Using the weight mentioned above, we summed over the annual expenditures on these payments to calculate debt for each household.

4.3.3.2 Effects on Lower-Income Households

We use the CES data for the years 2007-2015 to classify households with before-tax incomes below the weighted median as "lower income," and the other half of households are considered "higher income." For example, the weighted medians in 2015 and 2014 were $50,000 and 48,465, in 2015$, respectively.

As we pointed out in the Draft TAR (Chapter 6.5.1), lower-income households are not the primary market for new vehicles. Figure 4.23 shows annual expenditures on new vehicles for lower-income households, as well as for higher-income households; it also includes median before-tax income. Lower-income households spend far less on vehicles than do higher-income households. For example, in 2015, lower-income households on average spent $911 on new vehicles, while higher-income households spent more than 3 times as much, $3,009. Greene and Welch (2016), using income quintiles, find similarly that lower-income households spend less on new and used vehicles than higher-income households.[T]

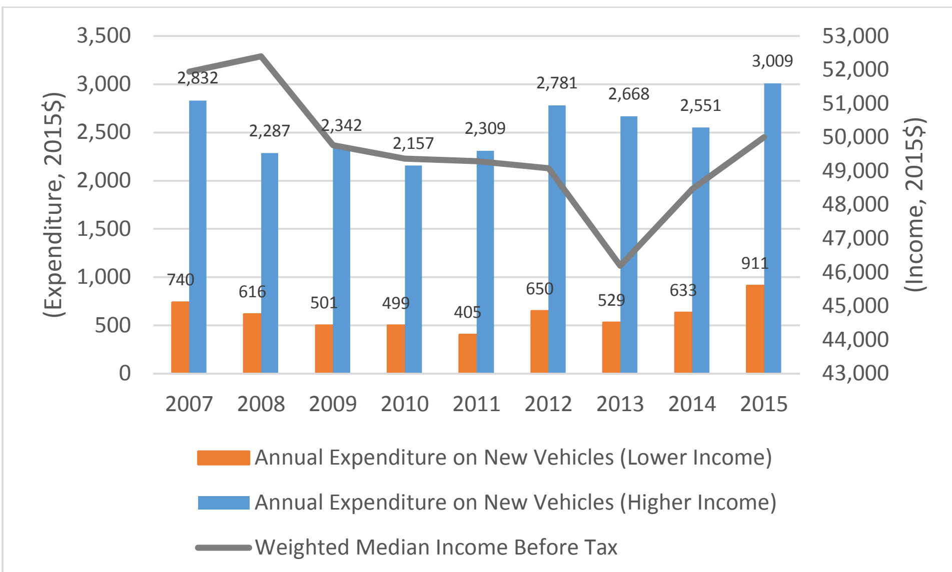


Figure 4.23 Median Income and Annual Expenditure on New Vehicles for Lower and Higher Income Households

Figure 4.24 shows the proportion of lower- and higher-income households that bought vehicles. A small proportion of households buy a vehicle, either new or used, in any one year. For instance, in 2015, 0.8 percent of lower-income households bought a new vehicle, and about 3.3 percent bought a used vehicle. About 2.4 percent of higher-income households bought a new vehicle, and about 4.6 percent of them bought used vehicles. While a higher proportion of both income groups buy used vehicles than buy new vehicles, lower-income households buy fewer of

[T] Greene, David, and Jilleah Welch (2016). "The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the United States." University of Tennessee Baker Center Report 5:16, Docket EPA-HQ-OAR-2015-0827-4311.

both. Perhaps worth noting in this chart is that the proportion of households buying vehicles, either new or used, has increased, albeit slightly, since 2012, when the National Program began. As with sales, discussed in Section B.1.3 of the Proposed Determination Appendix, this increase is likely to be due more to economic recovery than to the National Program.

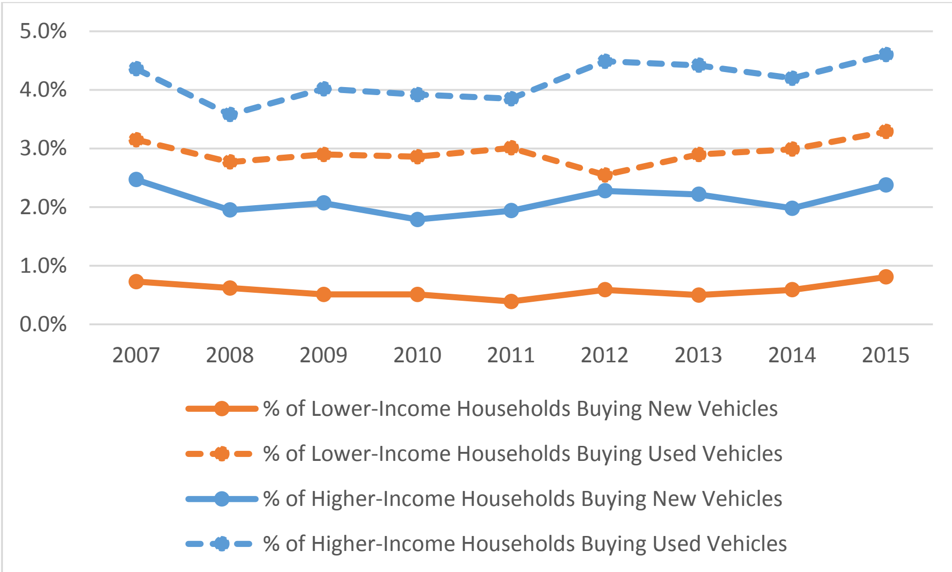


Figure 4.24 Percentage of Lower-Income and Higher-Income Households Buying New and Used Vehicles

Figure 4.25 compares annual expenditures on new vehicles, used vehicles, and fuel for lower-income households in Panel A, and higher-income households in Panel B, from the CES data. As Consumer Federation of America has pointed out, lower-income households spend more on gasoline than they do on either new or used vehicles, and they spend more on used vehicles than they do on new vehicles. As the figure shows, higher-income households spend more on new than on used vehicles; in 2015, their expenditures on fuel approximately equaled expenditures on new and used vehicles. In addition, household expenditures on gasoline and motor oil fluctuates more than its expenditures on new and used vehicles. This suggests that households may face more uncertainty due to changes in fuel prices than they do due to changes in vehicle prices. Greene and Welch estimate that increased fuel economy decreased fuel expenditures by about 30 percent between 1980 and 2014, with most of that reduction before the mid-1990s; they attribute almost flat expenditures since then to the increase in the proportion of light trucks over time.[60] They observe that lower-income households lag behind higher-income households in getting these reductions, because it takes time for the more efficient vehicles to become part of the used vehicle market. They also estimate that used vehicle prices decrease faster than vehicle VMT, so that the payback period for used vehicles should decrease as vehicle age.

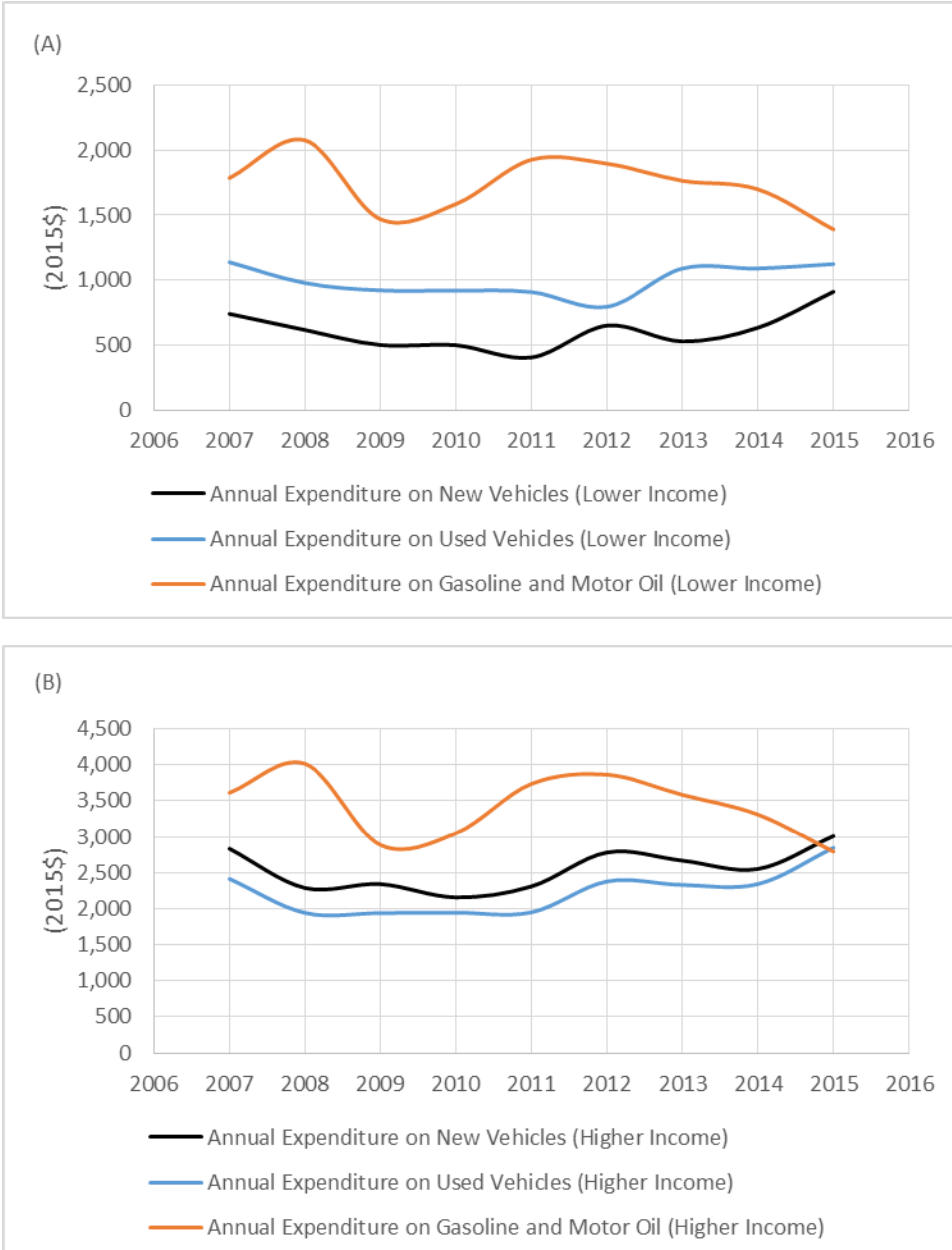


Figure 4.25 Annual Expenditure on Vehicles and Gasoline for Lower-Income Households (A) and Higher-Income Households (B)

These data suggest that lower-income households are more affected by the impact of the standards on the used vehicle market than on the new vehicle market.

4.3.3.3 Effect of the Standards on the Used Vehicle Market

The effects of the standards on lower-income households depends on its impacts, not only in the new vehicle market, but also in the used vehicle market. The effect of the standards on the used vehicle market will be related to the effects of the standards on new vehicle prices, the fuel efficiency of new vehicle models, the fuel efficiency of used vehicles, and the total sales of new vehicles. If the consumer value of fuel savings resulting from improved fuel efficiency outweighs the average increase in new models' prices to potential buyers of new vehicles, sales of new vehicles could rise, and the used vehicle market may increase in volume as new vehicle buyers sell their older vehicles. In this case, lower-income households are likely to benefit from the increased availability of used vehicles. However, if potential buyers value future fuel savings resulting from the increased fuel efficiency of new models at less than the increase in their average selling price, sales of new vehicles could decline, and the used vehicle market may decrease in volume as people hold onto their vehicles longer. In this case, lower-income households could face increased costs due to reduced availability of used vehicles.

Figure 4.26 presents data from the Consumer Price Index for used cars and trucks and new vehicles.[U] Each series has been adjusted to a year 2015 reference case with underlying prices in 2015$ so that numbers on the *y*-axis represent the percentage difference from price levels in 2015. Prices of used cars and trucks have decreased since 1995, and have varied in a small range between 2008 and 2015. As can be seen, the used cars and trucks price index closely follows the new vehicles price index, although used cars and trucks prices have a bit more volatility across all years. It is difficult, if not impossible, to estimate what prices for used cars and trucks would have been in the absence of the standards. These trends are likely to be affected by the increased durability of vehicles and the recession. As with the effects of the standards on new vehicle sales, it is possible that the GHG/fuel economy standards have had some influence on these trends, but their effect is likely swamped by the effects of the economic recovery.

[U] The Consumer Price Index computes the average change in prices over time for a "market basket" of consumer goods and services. Both the used cars and trucks index as well as the new vehicles index are components of the private transportation index, and also feed into the transportation group of the CPI. To construct the used cars and trucks index, BLS obtains price data from the National Automobile Dealers Association Official Used Car Guide, and then adjusts for both quality and depreciation. The new vehicles index uses price information from BLS surveys of dealerships and is also adjusted for quality. See http://www.bls.gov/cpi/cpifacuv.htm and http://www.bls.gov/cpi/cpifacnv.htm for more information.

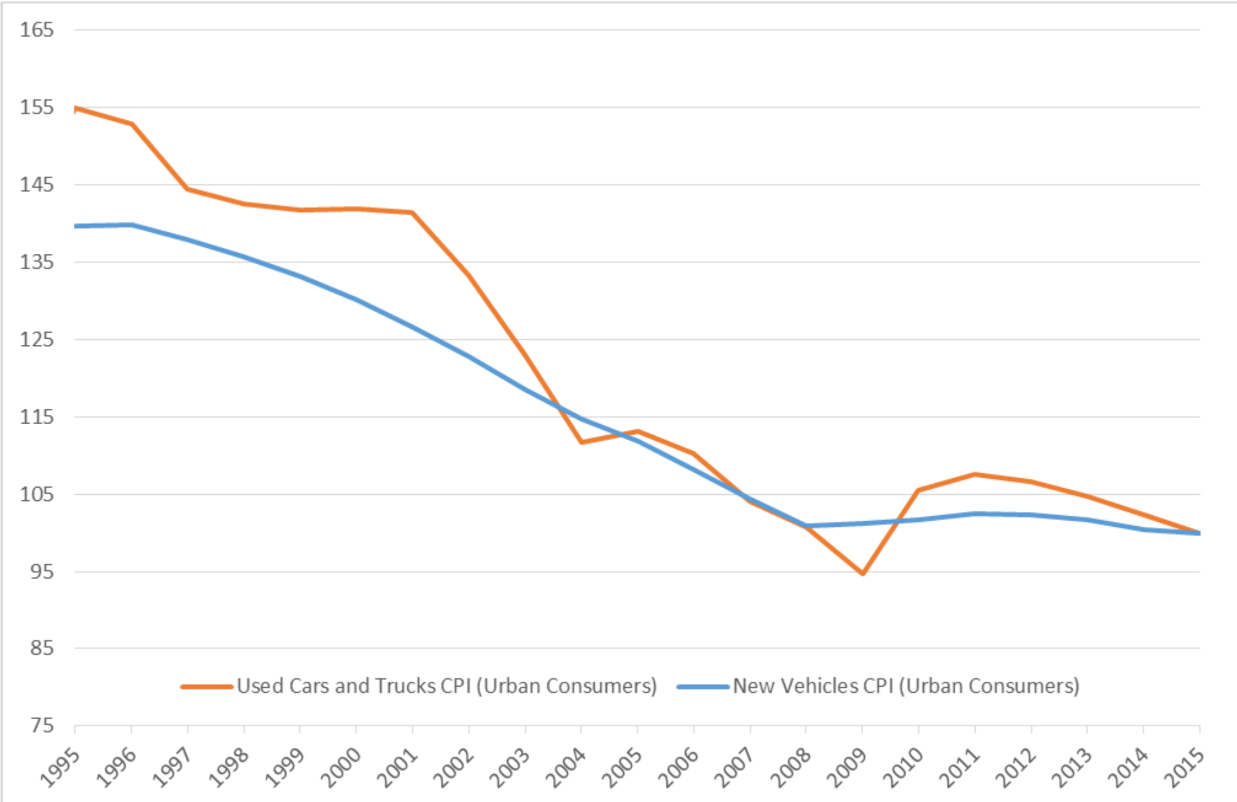


Figure 4.26 Used and New Vehicle Consumer Price Index, 2015 = 100 (2015$)

4.3.3.4 Effects on Access to Credit

Another question is whether higher vehicle prices may be excluding some prospective consumers from the new vehicle market through effects on consumers' ability to finance vehicles. It is possible that lenders focus solely on the amount of the vehicle loan, the person's current debt, and the person's income when issuing loans, and not the costs associated with fuel consumption. If lenders in fact restrict themselves to consideration of only those three factors, and fuel savings are not factored in to counter-balance this cost, then the higher up-front costs of new vehicles subject to the standards would reduce buyers' ability to get loans. This may occur even though, as discussed in Proposed Determination Appendix Section C.2.4, the fuel savings exceed the increased loan payments and other costs in the first year of loans with 5 or more year duration. Thus, if lenders do not take fuel savings into account in providing loans, households that are borrowing near the limit of their abilities to borrow will either have to change what vehicles they buy, or not buy vehicles at all.

On the other hand, some evidence suggests that the loan market may evolve to take fuel savings into greater account in the lending decision. Market innovation suggests that parts of the loan market take fuel savings into account in the lending decision. Some lenders currently give discounts for loans to purchase more fuel-efficient vehicles.[61] An internet search on the term "green auto loan" produced more than 60 lending institutions that provide reduced loan rates for more fuel-efficient vehicles.[62] A third of credit unions responding to a recent survey offered some type of green auto loan.[63] In a survey of nine credit unions, the ratio of the dollar value of green loans to total loans varied between 0.09 and 33.89 percent.[64] It is possible that the auto loan market may evolve to include further consideration of fuel savings, as those savings are a significant factor in offsetting the increase in up-front costs of vehicles.

Next, we examine the question of whether the debt-to-income ratio (DTI) is an impassible obstacle for lending, because of the importance of the DTI in determining access to credit. The analysis that follows is based on guidance from several online sources stating that most lenders avoid giving loans to consumers who have over 36 percent DTI.[65] We use CES data pooled across 2007-2015 to examine households with over 36 percent DTI in order to gauge whether exceeding this threshold may preclude households from being able to finance a vehicle purchase. The components included in our DTI calculation are derived from those same online sources cited above (Bankrate.com, Zillow.com, and TheNest.com). These components are mortgage payments, home equity loan payments, monthly rent, other vehicle payments, child support, and alimony

The results in Table 4.6 show that, from 2007 to 2015, 28 percent of lower-income households and 7 percent of higher-income households who both had a DTI of over 36 percent and purchased at least one new vehicle financed their vehicle purchases. The results are similar using a 40 percent DTI, the threshold used in an analysis by Wagner et al. (2012), as reported in Table 4.7.[66] This suggests that the DTI is not an inflexible barrier. Thus, if increases in vehicle prices push some households over the 36 or 40 percent DTI, it nevertheless may be possible for them to get loans.

Table 4.6 Breakdown of Households That Bought at Least One New Vehicle By the Cutoff of DTI Ratio 36%, 2007-2015

	Lower Income	Higher Income
< or equal to 36% DTI	72%	93%
>36% DTI	28%	7%

Table 4.7 Breakdown of Households That Bought At Least One New Vehicle by the Cutoff of DTI Ratio 40%, 2007-2015

	Lower Income	Higher Income
< or equal to 40% DTI	76%	95%
>40% DTI	24%	5%

In addition, we look at the trends in percentage of lower-income and higher-income households who had DTI ratios larger than 36 percent and were able to purchase at least one new vehicle with an auto loan. As shown in Figure 4.27, while lower-income households with higher DTI ratios have been able to get loans to buy new vehicles through the years, the percentage of lower-income households who got the loans varies more than that of higher-income households. It is worth noting that other factors, such as interest rates and lending policies of financial institutions, also affect the credit-worthiness of households. EPA does not expect the standards to have any measurable effect on interest rates, which are determined primarily by broader macroeconomic factors.

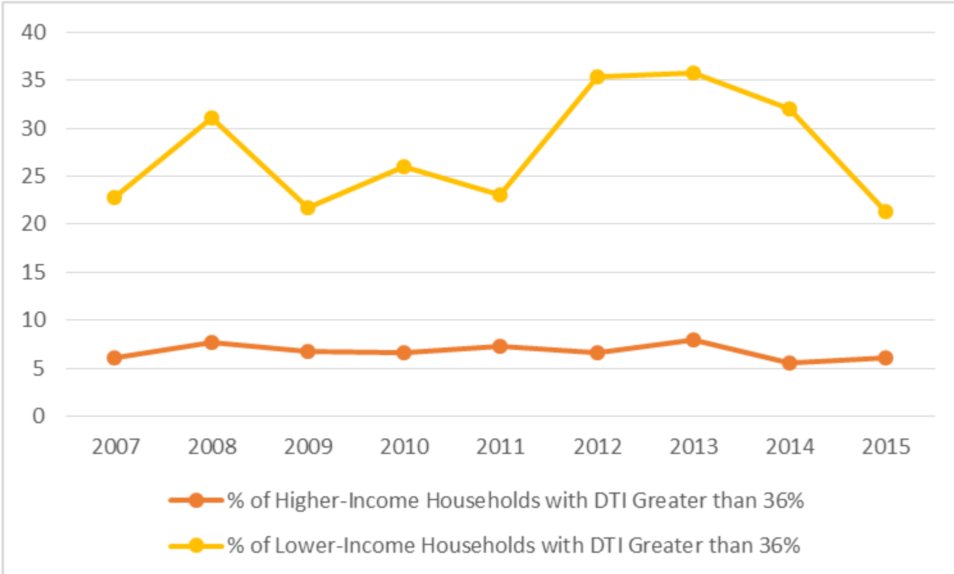


Figure 4.27 Percentage of Households Buying at Least One New Vehicle with Finance who had Debt-to-Income (DTI) Ratio Greater than 36 Percent

4.3.3.5 Effects on Low-Priced Vehicles

Low-priced vehicles may be considered an entry point for people into buying new vehicles instead of used ones; automakers may seek to entice people to buy new vehicles through a low price point. Commenters have expressed concern that higher costs associated with the standards could affect the ability of automakers to maintain vehicles in this segment.

The cutoff for a car to be "lower-priced" is a matter of opinion. We searched the web for definitions. CNN Money, in 2003, defined a “cheap” car as one with a price less than $12,500 ($15,900 in 2015$).[67] Motor Trend (2015) and Auto Bytel (2015)defined the lowest market segment as those $15,000 or less.[68] U.S. News and World Report (2015) considered “affordable” cars to be priced from under $20,000 to under $40,000.[69] Consumer Reports (2015) used the cutoff of $25,000 to characterize cars in the lower priced market segment.[70] Of websites that mention or rank affordable or low-priced vehicles, the highest price in the "affordable" category varies. For example, for 2014 and 2015, we found highest-priced models of $14,845.00 (Autobytel 2015), $14,850 (Lloyd-Miller, 2015), and $19,890 (Notte, 2014).[71] Based on this review, we use a cutoff of $15,000 (2015$) to identify low-priced vehicles.

We use Ward’s Automotive data for U.S. cars for the years 2007-2015 to examine the impacts of the standards on the costs of the low-priced segment of the market.[72] Figure 4.28 shows the number of models available for less than $15,000 (2015$). The number of available low-priced models available has ranged from 8 to 18 model trims, with 13 trims available in 2015. Automakers appear to be able to provide low-priced vehicles; this graph does not indicate whether it has become more challenging to do so.

Figure 4.28 Number of <$15,000 (2015$) Vehicle Model Trims Available

Figure 4.29 shows the minimum MSRP (in 2015$) for all new vehicles over time. It indicates that the least costly (always cars) have become more expensive since 2001. This finding suggests that these vehicles may be becoming more costly to produce, though it leaves open the question of why.

We next sought to understand whether quality increases might affect these price changes. Table 4.8 shows, as an example, the features of the Nissan Versa over time. The Nissan Versa was chosen since it was the lowest-priced vehicle in 2016 (according to the MSRP of the base model sedan) and in 6 of the 9 years examined.[V] The MSRP data are from Ward's and are in 2015$;[73] all other data are from Edmunds.com.[74] Some content has increased over time, such as audio controls on the steering wheel and the auxiliary audio input. In contrast, the horsepower decreased between MY2008 and 2009. In constant dollars, the MSRP of the Nissan Versa is lower now than in 2007, though it has increased since its minimum value in MY2011.

[V] For MYs 2007 and 2008, the Chevrolet Aveo, and the Hyundai Accent Blue for MY2010, have lower MSRPs than the Versa, while not having more content.

Table 4.8 Features of the Nissan Versa over Time, Base Model (Edmund's and Ward's Automotive)

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
4-wheel ABS						x	x	x	x	x
Emergency Braking Assist						x	x	x	x	x
Stability Control						x	x	x	x	x
Traction Control						x	x	x	x	x
Auxiliary Audio Input						x	x	x	x	x
Bluetooth Wireless Datalink for Hands-free Phone									x	x
Audio Controls on Steering Wheel									x	x
Speed Sensitive Volume Control									x	x
Air Conditioning	x	x	x	x	x	x	x	x	x	x
Horsepower	122 hp @ 5200 rpm	122 hp @ 5200 rpm	107 hp @ 6000 rpm	107 hp @ 6000 rpm	107 hp @ 6000 rpm	109 hp @ 6000 rpm	109 hp @ 6000 rpm	109 hp @ 6000 rpm	109 hp @ 6000 rpm	109 hp @ 6000 rpm
MSRP (2015$)	14746	14660	11730	11614	11415	12270	13149	13169	12938	12962

In the past, not only was the low-priced vehicle segment a way to encourage first-time new vehicle purchasers, but it also tended to include more fuel-efficient vehicles that assisted automakers in achieving CAFE standards.[75] The footprint-based standards, by encouraging improvements in GHG emissions and fuel economy across the vehicle fleet, reduce the need for low-priced vehicles to be a primary means of compliance with the standards. This change in incentives for the marketing of this segment may contribute to the increases in the prices of vehicles previously in this category. In addition, as seen with the Versa example above, these vehicles may be gaining more content, such as improved entertainment systems and electric windows, if they develop an identity as a desirable market segment. For instance, the Nissan Versa, the lowest-priced vehicle since MY2011, added Bluetooth, audio controls on the steering wheel, and speed-sensitive volume control in MY2015. It may be that the small, fuel-efficient vehicles previously sold with low prices are evolving to fit consumer demand that prefers content to low prices.

In sum, the low-priced vehicle segment still exists. Whether it continues to exist, and in what form, may depend on the marketing plans of manufacturers: whether benefits are greater from offering basic new vehicles to first-time new-vehicle buyers, or from making small vehicles more attractive by adding more desirable features to them.

Figure 4.29 Minimum MSRP of All Car Models Available

4.3.4 Conclusion

It is difficult to determine how the LDV GHG standards have affected vehicle affordability thus far, due to both challenges in defining affordability, and difficulties in separating the effects of the standards from other market changes. Because lower-income households are most likely to buy used vehicles, the effects of the standards on lower-income households depend mostly on their effects on used vehicles. In the used-vehicle market, prices have not shown marked increases; the trend appears to be flat or decreasing. The effects of the standards on access to credit may not be large: there continue to be loan discounts for fuel-efficient vehicles, and many people, including lower-income people, with high debt-to-income ratios appear able to get loans. The low-priced vehicle segment still exists, perhaps in changing form, as it appears that manufacturers are improving the content features in this segment. In sum, if the standards thus far have affected vehicle affordability, they have not had significant visible effects. In addition, there appear to be market adjustments, such as ongoing changes in the finance market, that may mitigate some of any adverse effects. In the MY2022-2025 time frame, the primary effects on affordability of vehicle sales are still likely to be due to broader macroeconomic factors, such as economic activity and overall employment; any impacts of the standards are likely to be secondary to those broader economic factors.

This assessment has focused on the effects of the standards on purchase affordability of vehicles–that is, whether they become more difficult to purchase because of the increase in up-front costs. The vehicles will also become less expensive to operate, due to fuel savings from more fuel-efficient technologies. The reduced operating costs from fuel savings over time are still expected to exceed the increase in up-front vehicle costs, as discussed further in Section C.2.4 of the Proposed Determination Appendix, as a further mitigation of any effects on vehicle affordability.

REFERENCES

---

[1] 77 Federal Register 62843-62844 (October 15, 2012) and Regulatory Impact Analysis, pages 3-18 to 3-23.
[2] National Research Council. (2015) *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. The National Academies Press. pp. S-9, 9-2, 10-29, 10-38.
[3] National Research Council. (2015) *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. The National Academies Press. pp. S-9, 9-2, 10-29, 10-38.
[4] Knittel, C. R. (2011). "Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector." *American Economic Review* 101(7): pp. 3368–3399, Docket EPA-HQ-OAR-2010-0799-11946; Klier, T. and Linn, J. (2016). "The Effect of Vehicle Fuel Economy Standards on Technology Adoption." *Journal of Public Economics* 133: 41-63, Docket EPA-HQ-OAR-2015-0827-0142; McKenzie, D. and Heywood, J. B. (2015). "Quantifying efficiency technology improvements in U.S. cars from 1975-2009." *Applied Energy* 157: 918-928, Docket EPA-HQ-OAR-2015-0827-0147; Wang, Y. (2016). "The Impact of CAFE Standards on Automobile Innovation in the US." Working paper, Docket EPA-HQ-OAR-2015-0827-0133.
[5] Cooke, Dave (2016). "The Trade-off between Fuel Economy and Performance: Implications for the Mid-term Evaluation of the National Program." Union of Concerned Scientists working paper.
[6] Knittel, C. R. (2011). "Automobiles on Steroids: Product Attribute Trade-Offs and Technological Progress in the Automobile Sector." *American Economic Review* 101(7): pp. 3368–3399, Docket EPA-HQ-OAR-2010-0799-11946; Klier, T. and Linn, J. (2016). "The Effect of Vehicle Fuel Economy Standards on Technology Adoption." *Journal of Public Economics* 133: 41-63; McKenzie, D. and Heywood, J. B. (2015). "Quantifying efficiency technology improvements in U.S. cars from 1975-2009." *Applied Energy* 157: 918-928; Wang, Y. (2016). "The Impact of CAFE Standards on Automobile Innovation in the US." Working paper, Docket EPA-HQ-OAR-2015-0827-0127.
[7] MacKenzie, Don, and John Heywood (2012). "Acceleration Performance Trends and Evolving Relationship Between Power, Weight, and Acceleration in U.S. Light-Duty Vehicles." *Transportation Research Record* 2287: 122-131, Docket EPA-HQ-OAR-2015-0827-0148,.
[8] Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2003). Technological change and the environment. In *Handbook of environmental economics 1*, ed. K.-G. Maler and J. R. Vincent. Elsevier, Docket EPA-HQ-OAR-2015-0827-0130.
[9] Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2003). Technological change and the environment. In *Handbook of environmental economics 1*, ed. K.-G. Maler and J. R. Vincent. Elsevier, Docket EPA-HQ-OAR-2015-0827-0130.
[10] Dosi, G. and Nelson, R. R. (2010). "Technical Change and Industrial Dynamics as Evolutionary Processes." *Handbook of Econometrics 1*: pp. 52–114.
[11] Abernathy, W. J., and Utterback, J. M. (1978). Patterns of industrial innovation. *Technology review*, 80, pp. 254–228; Henderson, R. M., and Clark, K. B. (1990). "Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms." *Administrative science quarterly*, 9-30.
[12] Zhao, H. (Ed.). (2009). *Advanced Direct Injection Combustion Engine Technologies and Development: Gasoline and Gas Engines (Vol. 1).* ISBN 9781845697327. Elsevier. pp. 1-3.
[13] U.S. EPA. (2016). Report Tables for Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2016, EPA Report 420-R-16010-report-tables.xlsx, Table 5.3.1, https://www.epa.gov/fuel-economy/download-co2-and-fuel-economy-trends-report-1975-2016 , accessed 11/8/2016. There are similar examples from the stationary source world. See 80 FR at 64575 (Oct. 23, 2015) and Laney, Mike (2015). " History of Flue Gas Desulfurization in the United States- 1970-1976," memo to Rulemaking Docket ID EPA-HQ-OAR-2013-0495-11774, demonstrating the role of regulatory standards in the development and deployment of scrubber technology.
[14] Blumstein, Carl and Margaret Taylor (2013). "Rethinking the Energy-Efficiency Gap: Producers, Intermediaries, and Innovation," Energy Institute at Haas Working Paper 243, University of California at Berkeley, Docket EPA-HQ-OAR-2014-0827-0075; Tirole, Jean (1998). The Theory of Industrial Organization. Cambridge, MA: MIT Press, pp. 400, 402, Docket EPA-HQ-OAR-2014-0827-0089.
[15] Gal-Or, E. (1987). "First Mover Disadvantages with Private Information." *The Review of Economic Studies* 54(2): pp. 279–292; Liu, Z. (2005). "Stackelberg Leadership with Demand Uncertainty." *Managerial and Decision Economics* 26: pp. 345–350.
[16] Popp, D., Newell, R. G., and Jaffe, A. B. (2010). "Energy, the environment and technological change." In *Handbook of the economics of innovation 2*, ed. B. H. Hall, and N. Rosenberg. Elsevier.

---

[17] Holmes, T. J., Levine, D. K., and Schmitz, J. A., Jr. (2012). “Monopoly and the Incentive to Innovate When Adoption Involves Switchover Disruptions.” *American Economic Journal: Microeconomics* 4(3): pp. 1-33.
[18] National Research Council. (2015) *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. The National Academies Press. pp. S-9, 9-2, 10-29, 10-38; Klier, T. and Linn, J. (2016). “The Effect of Vehicle Fuel Economy Standards on Technology Adoption.” *Journal of Public Economics* 133: 41-63; Wang, Y. (2016). “The Impact of CAFE Standards on Automobile Innovation in the US.” Working paper.
[19] Boncimino, A. (April 10, 2015). “Auto industry rushes to meet 2025 fuel efficiency guidelines.” *Upstate Business Journal*. http://upstatebusinessjournal.com/news/auto-industry-rushes-meet-2025-fuel-efficiency-guidelines/ ; Buchholz, K. (March 13, 2015). “New technology for exhausting jobs.” *Automotive Engineering Magazine*. http://articles.sae.org/13974/ ; Truett, Richard (November 15, 2016). "With nod to EPA, today's cars are faster, more powerful and more fun to drive." Automotive News, http://www.autonews.com/article/20161115/BLOG06/161119909/with-nod-to-epa-todays-cars-are-faster-more-powerful-and-more-fun-to.
[20] Powell, W. W., and Giannella, E. (2010). “Collective Invention and Inventor Networks,” In *Handbook of the Economics of Innovation*, Volume 1. Ed. B. Hall and N. Rosenberg Elsevier.
[21] Greene, David, and Jin-Tan Liu (1988). “Automotive Fuel Economy Improvements and Consumers’ Surplus.” *Transportation Research A* 22A(3): 203-218. Docket EPA-HQ-OAR-2010-0799-0703.
[22] Greene, David (2010). “How Consumers Value Fuel Economy: A Literature Review.” EPA-420-R-10-008. Docket EPA-HQ-OAR-2010-0799-0711.
[23] Greene, David, Anushah Hossein, and Robert Beach (2016). "Consumer Willingness to Pay for Vehicle Attributes: What is the Current State of Knowledge?" RTI International Final Report, Work Assignment 4-11, EPA Contract EP-C-11-045.
[24] Greene, David (2010). “How Consumers Value Fuel Economy: A Literature Review.” EPA-420-R-10-008. Docket EPA-HQ-OAR-2010-0799-0711.
[25] McAlinden, Sean, et al. (2016). "The Potential Effects of the 2017-2025 EPA/NHTSA GHG/Fuel Economy Mandates on the U.S. Economy." Center for Automotive Research http://www.cargroup.org/?module=Publications&event=View&pubID=143 , accessed 10/11/2016.
[26] Isenstadt, Aaron (2016). "The latest paper by the Center for Automotive Research is not what it thinks it is." International Council on Clean Transportation, http://www.theicct.org/blogs/staff/latest-paper-by-CAR-is-not-what-it-thinks-it-is , accessed 10/13/2016; Cooke, Dave (2016). "Déjà vu: Shoddy Economic study Touted by Automakers Flaunts Facts." Union of Concerned Scientists, http://blog.ucsusa.org/dave-cooke/deja-vu-shoddy-economic-study-touted-by-automakers-flaunts-facts, accessed 10/19/2016.
[27] Isenstadt, Aaron (2016). "The latest paper by the Center for Automotive Research is not what it thinks it is." International Council on Clean Transportation, http://www.theicct.org/blogs/staff/latest-paper-by-CAR-is-not-what-it-thinks-it-is , accessed 10/13/2016; Cooke, Dave (2016). "Déjà vu: Shoddy Economic study Touted by Automakers Flaunts Facts." Union of Concerned Scientists, http://blog.ucsusa.org/dave-cooke/deja-vu-shoddy-economic-study-touted-by-automakers-flaunts-facts, accessed 10/19/2016. Greene, David (1991). "Short-Run Pricing Strategies to Increase Corporate Average Fuel Economy." Economic Inquiry 29(1): 101-114.
[28] National Research Council. (2015) *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. The National Academies Press.
[29] Berck, Peter, and Sandra Hoffmann (2002). "Assessing the Employment Impacts of Environmental and Natural Resource Policy." Environmental and Resource Economics 22: 133-156 (in particular, p. 145). Docket EPA-HQ-OAR-2010-0799-0678.
[30] National Research Council. (2015) *Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles*. The National Academies Press, pp. 9-16, 9-36.
[31] Huang, Hsing-Hsiang, and Gloria Helfand (2016). "Memorandum: Content Analysis of Auto Reviews using MY2014 and MY2015 Data." U.S. EPA Office of Transportation and Air Quality, Memorandum to Docket.
[32] Sha, Mandy, Amanda Smith, and Robert Beach (2016). “Content Analysis of Professional Automotive Reviews: Model Year 2015, Work Assignment 4-08 Final Report.” RTI International.
[33] Cassidy, Alecia, Geoffrey Burmeister, and Gloria Helfand. "Impacts of the Model Year 2017-25 Light-Duty Vehicle Greenhouse Gas Emission Standards on Vehicle Affordability." Working paper, docket EPA-HQ-OAR-2015-0827-0401.
[34] Hancock, K.E. (1993). “‘Can’t Pay? Won’t Pay?’ or Economic Principles of ‘Affordability’.” Urban Studies 30(1): 127—145.
[35] Quigley, J.M., and Raphael, S. (2004). “Is Housing Unaffordable? Why Isn’t It More Affordable?” The Journal of Economic Perspectives 18(1): 191—214.

[36] Bradley, R. (2008). "Comment – Defining health insurance affordability: Unobserved heterogeneity matters." Journal of Health Economics 27: 1129—1140.
[37] Bartl, M. (2010). "The Affordability of Energy: How Much Protection for the Vulnerable Consumers?" Journal of Consumer Policy 33: 225—245.
[38] Fankhauser, S., and Tepic, S. (2007). "Can poor consumers pay for energy and water? An affordability analysis for transition countries." Energy Policy 35: 1038-1049.
[39] Blaylock, J. et al. (1999). "Economics, food choices, and nutrition." Food Policy 24: 269—286.
[40] Glied, S. (2009). "Mandates and the Affordability of Health Care." Inquiry 46: 203—214.
[41] Milne, C. (2000). "Affordability of basic telephone service: an income distribution approach." Telecommunications Policy 24: 907—927.
[42] Haffner, M., and Heylen, K. (2011). "User Costs and Housing Expenses: Towards a More Comprehensive Approach to Affordability." Housing Studies 26(4): 5930—614.
[43] Bramley, G. (1990). "Access, affordability and housing need." Paper presented at ESRC Housing Studies Conference, University of Surrey, September 1990. Mimeograph, SAUS, University of Bristol. In Hancock, K.E. (1993). 'Can Pay? Won't Pay?' or Economic Principles of 'Affordability'. Urban Studies 30(1): 127—145.
[44] Whitehead, C.M.E. (1991). "From need to affordability: An analysis of UK housing objectives," Urban Studies 28(6): 871—887.
[45] Hancock, K.E. (1993). "'Can't Pay? Won't Pay?' or Economic Principles of 'Affordability'." Urban Studies 30(1): 127—145.
[46] Stone, M.E. (2006). "What is housing affordability? The case for the residual income approach." Housing Policy Debate 17(1): 151—184.
[47] U.S. Department of Housing and Urban Development (2015). "Affordable Housing." http://portal.hud.gov/hudportal/HUD?src=/program_offices/comm_planning/affordablehousing/ , accessed 8/26/2015.
[48] U.S. Department of Housing and Urban Development (2011). "Worst case housing needs 2011 Report to Congress," accessed 05/20/2014 at: http://www.huduser.org/Publications/pdf/HUD-506_WorstCase2011.pdf ; Steffen, B. L.; Carter, G.R.; Martin, M.; Pelletiere, D.; Vandenbroucke, D.A.; and Yao, Y.G.D. (2015). "Worst Case Housing Needs: 2015 Report to Congress." Department of Housing and Urban Development. Accessed 8/24/2015 at http://www.huduser.org/portal/publications/affhsg/wc_HsgNeeds15.html
[49] Bogdon, A.S., and Can, A. (1997). "Indicators of local housing affordability: Comparative and spatial approaches." Real Estate Economics 25(1): 43—80.
[50] Gan, Q., and Hill, R.J. (2009). "Measuring housing affordability: Looking beyond the median." Journal of Housing Economics 18: 115—125.
[51] Fisher, L.M., Pollakowski, H.O., and Zabel, J. (2009). "Amenity-based housing affordability indexes." Real Estate Economics 37: 705—746.
[52] Lerman, D.L., and Reeder, W.J. (1987). "The affordability of adequate housing." AREUEA Journal 15(4): 389—404.
[53] Thalmann, P. (1999). "Identifying households which need housing assistance." Urban Studies 36(11): 1933—1947.
[54] Thakuriah, P., and Liao, Y. (2006). "Transportation expenditures and ability to pay." Transportation Research Record: Journal of the Transportation Research Board 1985: 257—265.
[55] Bundorf, M.K., and Pauly, M.V. (2009). "Reply to Ralph Bradley, 'Comment – Defining health insurance affordability: Unobserved heterogeneity matters'." Journal of Health Economics 28: 251—254.
[56] Schanzenbach, D.W., and McGranahan, L. (2012). "The impact of transportation on affordability: An analysis of auto cost white paper." Manhattan Strategy Group, accessed 06/09/2014 at: http://www.locationaffordability.info/downloads/AutoCostResearch.pdf.
[57] U.S. Bureau of Labor Statistics. "Consumer Expenditure Survey," accessed 8/25/2015 at: http://www.bls.gov/cex/.
[58] Goldberg, P.K. (1996). "Dealer price discrimination in new car purchases: Evidence from the Consumer Expenditure Survey." Journal of Political Economy 104(3): 622—654.
[59] Yurko, A.V. (2011). "Heterogeneous Consumers: How the demand affects outcomes in vertically differentiated markets." Dissertation, University of Texas at Austin. http://www.lib.utexas.edu/etd/d/2008/yurkod66028/yurkod66028.pdf.
[60] Greene, David, and Jilleah Welch (2016). "The Impact of Increased Fuel Economy for Light-Duty Vehicles on the Distribution of Income in the United States." University of Tennessee Baker Center Report 5:16, Docket EPA-HQ-OAR-2015-0827-4311.

[61] Ladika, S. (2009). "Green auto loans offer lower rates," Bankrate.com, accessed 7/29/2015 at: http://www.bankrate.com/finance/auto/green-auto-loans-offer-lower-rates-1.aspx. Docket EPA-HQ-OAR-2010-0799-11829.
[62] Huang, Hsing-Hsiang, and Gloria Helfand (2016, November). "Memorandum: Lending Institutions that Provide Discounts for more Fuel-Efficient Vehicles." U.S. EPA Office of Transportation and Air Quality, Memorandum to Docket.
[63] Baumhefner, M. (2013). "Why Can't Your Loan be as Green and Efficient as Your Vehicle?" Natural Resources Defense Council Website, accessed 7/29/2015 at: http://switchboard.nrdc.org/blogs/mbaumhefner/why_cant_your_loan_be_as_green.html.
[64] Hall, W. R. (2011). "Finding Sustainable Profits: Green Lending in Credit Unions," Filene Research Institute, accessed 8/25/2015 at: https://filene.org/assets/pdf-reports/249_Hall_Finding_Sustainable_Profits.pdf.
[65] Bankrate (2015). "Debt-to-income ratio calculator." Bankrate.com, accessed 8/25/2015 at: http://www.bankrate.com/calculators/mortgages/ratio-debt-calculator.aspx ; Zillow (2015). "Debt-to-income calculator," Zillow.com, accessed 8/25/2015 at: http://www.zillow.com/mortgage-calculator/debt-to-income-calculator/ ; Keythman, B. (2015). "What is the 28-36 Rule of Debt Ratio?" Demand Media, accessed 8/25/2015 at: http://budgeting.thenest.com/28-36-rule-debt-ratio-22412.html.
[66] Wagner, D., P. Nusinovich, and E. Plaza-Jennings, National Automobile Dealers Association (February 13, 2012). ''The Effect of Proposed MY2017–2025 Corporate Average Fuel Economy (CAFE) Standards on the New Vehicle Market Population.''Docket EPA-HQ-OAR-2010-0799-9575, http://www.nadafrontpage.com/upload/wysiwyg/The%20Effect%20of%20Proposed%20MY%202017-2025%20CAFE%20Standards%20on%20New-Vehicle%20Market.pdf , accessed 10/27/2016.
[67] Isidore, C. (2003). "Cheap cars? Guess who sells the most." CNN Money, accessed 8/25/2015 at: http://money.cnn.com/2003/11/07/pf/autos/cheap_cars/.
[68] Motor Trend (2015). "New Cars," Motor Trend.com, accessed 8/25/2015 at: http://www.motortrend.com/new_cars/ ; Autobytel (2015). "Top 10 Least Expensive Coupes and Compact Cars." accessed 8/25/2015 at: http://www.autobytel.com/top-10-cars/least-expensive-cars/coupes/.
[69] U.S. News and World Report (2015). "Best Car Rankings," accessed 8/25/2015 at: http://usnews.rankingsandreviews.com/cars-trucks/rankings/cars/.
[70] Consumer Reports (2015). "Best new cars for under $25,000," accessed 8/25/2015 at: http://www.consumerreports.org/cro/2012/12/best-new-cars-for-under-25-000/index.htm
[71] Autobytel (2015). "Top 10 Least Expensive Coupes and Compact Cars." accessed 8/25/2015 at: http://www.autobytel.com/top-10-cars/least-expensive-cars/coupes/ ; Lloyd-Miller, J. (2015). "10 of the Most Affordable Cars for 2015," Cheatsheet, accessed 8/25/2015 at: http://www.cheatsheet.com/automobiles/10-of-the-most-affordable-cars-for-2015.html/?a=viewall ; Notte, J. (2014). "10 Most Affordable Cars Of 2014." The Street, accessed 8/25/2015 at: http://www.thestreet.com/story/12820361/1/10-most-affordable-cars-of-2014.html .
[72] Ward's Automotive Group (2007-2015). "Model U.S. Car and Light Truck Specifications and Prices." UsaVs01_2007.xls through UsaVx01_2015.xls.
[73] Ward's Automotive Group (2007-2015). "Model U.S. Car and Light Truck Specifications and Prices." UsaVs01_2007.xls through UsaVx01_2015.xls.
[74] Edmund's (2015). "2007 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2007/st-100840658/features-specs/ ; "2008 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2008/features-specs/; "2009 Nissan Versa - Features & Specs,." accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2009/features-specs/ ; "2010 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2010/features-specs/ ; "2011 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2011/features-specs/ ; "2012 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2012/features-specs/ ; "2013 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2013/features-specs/ ; "2014 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2014/features-specs/ ; "2015 Nissan Versa - Features & Specs," accessed 8/25/2015 at: http://www.edmunds.com/nissan/versa/2015/features-specs/ ; "2016 Nissan Versa Sedan - Features & Specs," accessed 11/1/2016 at http://www.edmunds.com/nissan/versa/2016/sedan/features-specs/.
[75] See, for example, Austin, David, and Terry Dinan (2005). "Clearing the Air: The Costs and Consequences of Higher CAFE Standards and Increased Gasoline." Journal of Environmental Economics and Management 50(3): 562—82; and Kleit, Andrew N. (2004). "Impacts of Long-Range Increases in the Fuel Economy (CAFE) Standard." Economic Inquiry 42(2): 279—294.

Table of Contents

Table of Figures

Table of Tables

Chapter 5: EPA's OMEGA Model

Applying technologies efficiently to the wide range of vehicles produced by various manufacturers is a challenging task. In order to assist in this task, EPA uses a computerized program called the Optimization Model for reducing Emissions of Greenhouse gases from Automobiles (OMEGA). Broadly, OMEGA starts with a description of the future vehicle fleet, including manufacturer, sales, base CO_2 emissions, footprint and the extent to which emission control technologies are already employed. For the purpose of this analysis, EPA uses OMEGA to analyze over 200 vehicle platforms which encompass approximately 1,300 vehicle models in order to capture the important differences in vehicle and engine design and utility of future vehicle sales of roughly 15-17 million units annually in the 2021-2025 timeframe.[A] The model is then provided with a list of technologies which are applicable to various types of vehicles, along with the technologies' cost and effectiveness and the percentage of vehicle sales which can receive each technology during the redesign cycle of interest. The model combines this information with economic parameters, such as fuel prices and a discount rate, to project how various manufacturers would apply the available technology in order to meet increasing levels of emission control. The result is a description of which technologies are added to each vehicle platform, along with the resulting cost. The model can also be set to account for various types of compliance flexibilities.[B]

EPA has described OMEGA's specific methodologies and algorithms previously in the model documentation,[1] the version of the model used for both the Proposed Determination and the Draft TAR is publically available on the EPA website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases, and it has been peer reviewed.[2]

5.1 OMEGA Overview

The OMEGA model evaluates the relative cost and effectiveness of available technologies and applies them to a defined vehicle fleet in order to meet a specified GHG emission target. Once the regulatory target (whether the target adopted in the rule, or an alternative target) has been met, OMEGA reports out the cost and societal benefits of doing so. The model is written in the C# programming language, however both inputs to and outputs from the model are provided using spreadsheet and text files. The output files facilitate additional manipulation of the results, as discussed in the next section.

OMEGA is primarily an accounting model. It is not a vehicle simulation model, where basic information about a vehicle, such as its mass, aerodynamic drag, an engine map, etc. are used to

[A] EPA's analysis fleet actually contains roughly 2,200 vehicle models, but many of those are the result of very minor differences in footprint and not truly different models.

[B] While OMEGA can apply technologies which reduce CO_2 efficiency related emissions and refrigerant leakage emissions associated with air conditioner use, this task is currently handled outside of the OMEGA core model. A/C improvements are highly cost-effective, and would always be added to vehicles by the model, thus they are simply added into the results at the projected penetration levels.

predict fuel consumption or CO_2 emissions over a defined driving cycle.[C] Although OMEGA incorporates functions which generally minimize the cost of meeting a specified CO_2 target, it is not an economic simulation model which adjusts vehicle sales in response to the cost of the technology added to each vehicle.[D]

OMEGA can be used to model either a single vehicle model or any number of vehicle models. Vehicles can be those of specific manufacturers as in this analysis or generic fleet-average vehicles as in the 2010 Joint Technical Assessment Report supporting the MY 2017-2025 NOI. Because OMEGA is an accounting model, the vehicles can be described using a relatively few number of terms. The most important of these terms are the vehicle's baseline CO_2 emission level, the level of CO_2 reducing technology already present, and the vehicle's "type," which indicates the technology available for addition to that vehicle to reduce CO_2 emissions. Information determining the applicable CO_2 emission target for the vehicle must also be provided. This may simply be vehicle class (car or truck) or it may also include other vehicle attributes, such as footprint.[E] In the case of this analysis, as in the Draft TAR, footprint and vehicle class are the relevant attributes.

Emission control technology can be applied individually or in groups, often called technology "packages," as discusses above. The OMEGA user specifies the cost and effectiveness of each technology or package for a specific "vehicle type," such as midsize cars with V6 engines or minivans. The user can limit the application of a specific technology to a specified percentage of each vehicle's sales (i.e., a "maximum penetration cap"), which for this analysis, are specified a priori by EPA. The effectiveness, cost, application limits of each technology package can also vary over time.[F] A list of technologies or packages is provided to OMEGA for each vehicle type, providing the connection to the specific vehicles being modeled.

OMEGA is designed to apply technology in a manner similar to the way that a vehicle manufacturer might make such decisions. In general, the model considers three factors which EPA believes are important to the manufacturer: 1) the cost of the technology, 2) the value which the consumer is likely to place on improved fuel economy and 3) the degree to which the technology moves the manufacturer towards achieving its fleetwide CO_2 emission target.

Technology can be added to individual vehicles using one of three distinct ranking approaches. Within a vehicle type, the order of technology packages is set by the OMEGA user. The model then applies technology to the vehicle with the lowest Technology Application Ranking Factor (hereafter referred to as the TARF). OMEGA offers several different options for calculating TARF values. One TARF equation considers only the cost of the technology and the value of any reduced fuel consumption considered by the vehicle purchaser. The other two TARF equations consider these two factors in addition to the mass of GHG emissions reduced

---

[C] Vehicle simulation models may be used in creating the inputs to OMEGA as discussed in Joint TSD Chapter 3 as well as Chapter 1 and 2 of the RIA.

[D] While OMEGA does not model changes in vehicle sales, RIA Chapter 8 discusses this topic.

[E] A vehicle's footprint is the product of its track width and wheelbase, usually specified in terms of square feet.

[F] "Learning" is the process whereby the cost of manufacturing a certain item tends to decrease with increased production volumes or over time due to experience. While OMEGA does not explicitly incorporate "learning" into the technology cost estimation procedure, the user can currently simulate learning by inputting lower technology costs in each subsequent redesign cycle based on anticipated production volumes or on the elapsed time.

over the life of the vehicle. Fuel prices by calendar year, vehicle survival rates and annual vehicle miles travelled with age are provided by the user to facilitate these calculations.

For each manufacturer, OMEGA applies technology (subject to penetration cap constraints) to vehicles until the sales and VMT-weighted emission average complies with the specified standard or until all the available technologies have been applied. The standard can be a flat standard applicable to all vehicles within a vehicle class (e.g., cars, trucks or both cars and trucks). Alternatively, the GHG standard can be in the form of a linear or constrained logistic function, which sets each vehicle's target as a function of vehicle footprint (vehicle track width times wheelbase). When the linear form of footprint-based standard is used, the "line" can be converted to a flat standard for footprints either above or below specified levels. This is referred to as a piece-wise linear standard, and was used in modeling the standards in this analysis.

The emission target can vary over time, but not on an individual model year basis. One of the fundamental features of the OMEGA model is that it applies technology to a manufacturer's fleet over a specified vehicle redesign cycle. OMEGA assumes that a manufacturer has the capability to redesign any or all of its vehicles within this redesign cycle. OMEGA does not attempt to determine exactly which vehicles will be redesigned by each manufacturer in any given model year. Instead, it focuses on a GHG emission goal several model years in the future, reflecting the manufacturers' capability to plan several model years in advance when determining the technical designs of their vehicles. Any need to further restrict the application of technology can be effected through the caps on the application of technology to each vehicle type mentioned above.

Once technology has been added so that every manufacturer meets the specified targets (or exhausts all of the available technologies), the model produces a variety of output files. These files include information about the specific technology added to each vehicle and the resulting costs and emissions. Average costs and emissions per vehicle by manufacturer and industry-wide are also determined for each vehicle class.

5.2 OMEGA Model Structure

OMEGA includes several components, including a number of pre-processors discussed above and a baseline vehicle forecast (see Chapter 1). The OMEGA core model collates this information and produces estimates of changes in vehicle cost and CO_2 emission level. Based on the OMEGA core model output, which now includes the technology penetration of the new vehicle mix, the scenario impacts (fuel savings, emission impacts, and other monetized benefits) are calculated via a post-processor called the OMEGA Inventory, Cost and Benefits Tool (ICBT) discussed in Section IV of the Proposed Determination. These pre- and post-processors and the OMEGA core model are available in the docket and on our website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

OMEGA is designed to be flexible in a number of ways. Very few numerical values are hard-coded in the model, and consequently, the model relies heavily on its input files. The model utilizes five input files: Market, Technology, Fuels, Scenario, and Reference. Figure 5.1 shows the (simplified) information flow through OMEGA, and how these files interact.

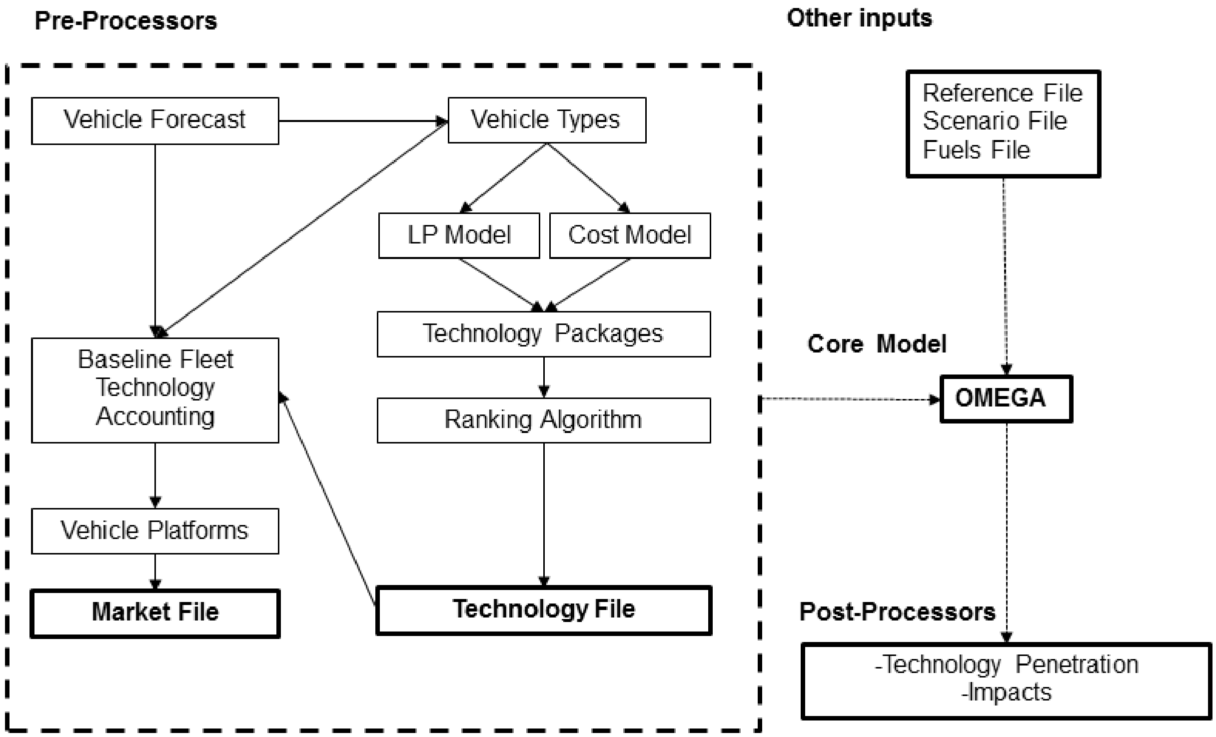


Figure 5.1 Information Flow in the OMEGA Model

OMEGA uses four basic sets of input data. The first, the market file, is a description of the vehicle fleet. The key pieces of data required for each vehicle are its manufacturer, CO_2 emission level, fuel type, projected sales and footprint. The model also requires that each vehicle be assigned to a particular vehicle type (currently, we use 29 vehicle types for reasons described above) which tells the model which set of technologies can be applied to that vehicle. Chapter 1 contains a description of how the market forecasts were created for modeling purposes. In addition, the degree to which each vehicle already reflects the effectiveness and cost of each available technology in the baseline fleet must be input. This prevents the model from adding technologies to vehicles already having these technologies in the baseline. It also avoids the situation, for example, where the model might try to add a basic engine improvement to a current hybrid vehicle.

The second type of input data, the technology file, is a description of the technologies available to manufacturers which consists primarily of their cost, effectiveness, compliance credit value, and electricity consumption. This file is generated by the Ranking algorithm and a post-processor tool which puts the Ranking algorithm output files into the proper format for OMEGA. In all cases, the order of the technologies or technology packages for a particular vehicle type is designated by the model user in the input files prior to running the model.

The third type of input data describes vehicle operational data, such as annual scrap rates and mileage accumulation rates, and economic data, such as fuel prices and discount rates. These estimates are described in Chapter 3 and are contained in the Reference, Fuels and Scenario input files.

The fourth type of data describes the CO_2 emission standards being modeled. These include the MY2021 standards and the MYs 2022-2025 standards. As described in more detail in

Chapter 5 of the joint TSD supporting the 2012 FRM, the application of A/C technology is evaluated in a separate analysis from those technologies which impact CO_2 emissions over the 2-cycle test procedure.[3] For modeling purposes, EPA applies this A/C credit by adjusting manufacturers' car and truck CO_2 targets by an amount associated with EPA's projected use of improved AC systems. The targets are specified in the Scenario input file along with details such as each scenario's name and the appropriate Market, Technology, Reference and Fuel file to use for each specific scenario. This is done exactly as done in the Draft TAR analysis.

The input files used in this analysis, as well as the current version of the OMEGA model, are available in the docket and on EPA's website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

5.3 OMEGA Pre-Processors, Vehicle Types & Packages

Individual technologies can be used by manufacturers to achieve incremental CO_2 reductions. However, EPA believes that manufacturers are more likely to bundle technologies into "packages" to capture synergistic aspects and reflect progressively larger CO_2 reductions with additions or changes to any given package. In addition, manufacturers typically apply new technologies in packages during model redesigns that occur approximately once every five years. This way, manufacturers can more efficiently make use of their redesign resources and more effectively plan for changes necessary to meet future standards.

Therefore, the approach taken by EPA is to group technologies into packages of increasing cost and effectiveness. Costs for the packages are a sum total of the costs for the technologies included. Importantly, the package costs and effectiveness represent those respective values relative to a "null" package of technologies. That "null" package consists of a fixed valve, port fuel injected engine mated to a 4 speed automatic transmission and having a declared 0 percent level of mass reduction. This "null" package is not meant to reflect an actual vehicle, but rather a technology "zero cost floor" or "zero effectiveness floor" from which costs and effectiveness of packages can be measured. This way, the technology package cost and effectiveness for the set of technologies on any actual vehicle can be determined relative to the null, an OMEGA package cost and effectiveness can then be calculated relative to the null, and the delta between the actual vehicle package and the OMEGA package can then be easily calculated. Effectiveness is somewhat more complex, as the effectiveness of individual technologies cannot simply be summed. To quantify the CO_2 (or fuel consumption) effectiveness, EPA relies on ALPHA and the Lumped Parameter Model, which are described in greater detail in Chapter 2 of this TSD.

5.3.1 Vehicle Types

As was done in the 2012 FRM and the Draft TAR, EPA uses "vehicle types" to represent the entire fleet in OMEGA. This was the result of analyzing the existing light-duty fleet with respect to vehicle size and powertrain configurations. In the past, all vehicles, including cars and trucks, were first distributed based on their relative size (i.e., vehicle class), starting from compact cars and working upward to large trucks. Next, each vehicle was evaluated for powertrain, specifically the engine size, I4, V6, and V8, then by valvetrain configuration (DOHC, SOHC, OHV), and finally by the number of valves per cylinder. We further designated some vehicle types as towing vehicle types and some as non-towing vehicle types. This towing/non-towing determination impacts the types of packages made available to specific vehicle within each vehicle type since only non-towing vehicle types are considered to be appropriate for electrification beyond strong HEV (i.e., to plug-in HEV or full BEV).

For this Proposed Determination, EPA has expanded the number of vehicle types from 19 to 29 to better characterize the fleet in terms of power-to-weight ratio, road load characteristics and size based on curb weight rather than a purely size-based market class definition. As a result, we no longer determine vehicle type based on whether a vehicle is a small car or a large SUV and, instead, make the determination in part based on its curb weight. We also make the determination based on the vehicle's power-to-weight ratio and road load characteristics or, in other words, its "ALPHA Class." This is described in more detail in Chapter 2.3.1.4 of the TSD. The implication to this change is a more appropriate determination of technology effectiveness and cost values than in past analyses. EPA believes that these 29 vehicle types broadly encompass the diversity in the fleet and that the analysis is appropriate for "average" vehicles.

As such, the six ALPHA classes (low, medium, and high vehicle power-to-weight levels, abbreviated as 'LPW', 'MPW', and 'HPW', respectively; the first two of these are divided further into low and high vehicle road load categories, abbreviated as 'LRL' and 'HRL', respectively), and the six curb weight classes (simply numbered 1 through 6 with 1 being the lightest curb weights and 5 the heaviest non-pickup curb weights; 6 is reserved for pickups) serve primarily to determine the effectiveness levels of new technologies by determining which input metrics are chosen within the lumped parameter model (see below). So, any vehicle models mapped into a LPW_HRL_3 vehicle type will get technology-specific effectiveness results for vehicles with low power-to-weight, high road load characteristics. Similarly, any such vehicles will get technology-specific costs, where applicable, for vehicles in curb weight class number 3, i.e., those costs developed on a weight basis such as advanced diesel, hybrid and other electrified powertrains and mass reduction. Note that most technology costs are not developed according to vehicle weight but are instead developed according to engine size, valvetrain configuration, etc. A detailed table showing the 29 vehicle types, their baseline engines, their descriptions and some example models for each is contained in the table below. Note that some models, specifically models with turbocharged engines or fueled by diesel fuel, are mapped into vehicle types whose description seems inaccurate. For example, the turbocharged Cruze (vehicle type 12) actually has an I4 DOHC engine, not a V6 DOHC engine. However, in OMEGA-space, such a vehicle operates as a V6 engine since its power and operating characteristics, its utility, is consistent with a V6 engine. Importantly, its effectiveness values will be consistent with a "LPW_LRL" ALPHA class and its costs values will be consistent with a turbocharged I4 in curb weight class 1. These characteristics are carefully tracked within OMEGA. That said, we will continue to study our classifications and may move toward vehicle types specifically for turbocharged vehicles in future analyses.

Table 5.1 Vehicle Types and Example Models

Vehicle Type	Description	Curb Weight Class	ALPHA Class	Example Models
1	I4 DOHC	1	LPW_LRL	Sentra, Corolla
2	I4 DOHC	1	MPW_LRL	Dart, Focus
3	I4 DOHC	2	MPW_LRL	Altima, Camry
4	I4 DOHC	2	LPW_HRL	Rogue, Patriot
5	I4 DOHC	3	MPW_LRL	Malibu, 200
6	I4 DOHC	3	LPW_HRL	Forester, Cherokee
7	I4 DOHC	4	LPW_HRL	Outback, Equinox
8	I4 DOHC	6	Truck	Colorado, Tacoma
9	V6 OHV	6	Truck	Silverado, Sierra
10	V6 SOHC	3	HPW	RDX, TLX
11	V6 SOHC	4	MPW_HRL	Odyssey
12	V6 DOHC	1	LPW_LRL	Cruze, Focus turbos
13	V6 DOHC	2	MPW_LRL	Fiesta turbo
14	V6 DOHC	2	LPW_LRL	Passat
15	V6 DOHC	3	HPW	E350, Impala, Q50
16	V6 DOHC	3	MPW_LRL	IS250
17	V6 DOHC	3	LPW_HRL	Transit
18	V6 DOHC	4	HPW	Charger
19	V6 DOHC	4	MPW_HRL	Pathfinder, Journey
20	V6 DOHC	5	HPW	Camaro
21	V6 DOHC	5	MPW_HRL	Grand Cherokee
22	V6 DOHC	6	Truck	Tacoma, Frontier
23	V8 OHV	5	HPW	Charger
24	V8 OHV	5	MPW_HRL	Tahoe, Suburban
25	V8 OHV	6	Truck	Silverado, Sierra
26	V8 DOHC	4	HPW	Mustang, SL550
27	V8 DOHC	5	HPW	QX80, GL550
28	V8 DOHC	5	MPW_HRL	GX460, Sequoia
29	V8 DOHC	6	Truck	Tundra, F150

Note: DOHC=dual overhead cam; SOHC=single overhead cam; OHV=overhead valve; Curb Weight Class is a percentile-based weight classification with 1 being the lightest and 6 being the heaviest vehicles; ALPHA class is described in Chapter 2 of the TSD and designates low/medium/high power-to-weight (L/M/HPW) and low/medium/high road load (L/M/HRL) or Truck which is used for pickups like the Ford F150 and Chevy Silverado.

5.3.2 Technology Packages, Package Building & Master-sets

Importantly, the effort in creating OMEGA packages attempts to maintain a constant utility and acceleration performance for each package as compared to the baseline package. As such, each package is meant to provide equivalent driver-perceived performance to the baseline package. There are two possible exceptions. The first is the towing capability of vehicle types which we have designated "non-pickups." This requires a brief definition of what we consider to be a towing vehicle versus a non-towing vehicle. Nearly all vehicles sold today, with the exception of the smaller subcompact and compact cars, are able to tow up to 1,500 pounds provided the vehicle is equipped with a towing hitch. These vehicles require no special OEM "towing package" of add-ons which typically include a set of more robust brakes and some additional transmission cooling. We do not consider such vehicles to be towing vehicles. Other vehicles a capable of towing up to 5,000 pounds, with the addition of a towing package, but are not heavy towing vehicles. We reserve the heavy-towing term for those vehicles capable of towing significantly more than 5,000 lbs. For example, a base model Ford Escape can tow 1,500 pounds while the V6 equipped towing version can tow up to 3,500 pounds. The former would not be considered a true towing vehicle while the latter would although it would not be considered a heavy-towing vehicle. The heavy-towing vehicles are those built, generally on a ladder frame and are generally pickup trucks. Vehicles mapped into those "Truck" vehicle types are considered heavy-towing vehicles and, as such, are not considered to be candidates for electrification beyond strong HEV.

We do not address towing at the vehicle level. Instead, we deal with towing at the vehicle type level. The importance of this distinction can be found in the types of hybrid and plug-in hybrid technologies we apply to towing versus non-towing vehicle types.[G] For the "Truck" vehicle types, we apply a P2 hybrid technology with a turbocharged and downsized gasoline direct injected engine. These packages are expected to maintain equivalent towing capacity to the baseline engine they replace. For the non-heavy towing vehicle types, we apply a P2 hybrid technology with a low-compression ratio Atkinson engine (not an Atkinson-2 engine) that has not been downsized relative to the baseline engine. This type of low-compression ratio Atkinson engine is used in the current Toyota Prius and Ford Escape hybrid and should not be confused with a high-compression ratio Atkinson 2 engine. We have maintained the original engine size (i.e., no downsizing) to maintain utility as best as possible, but EPA acknowledges that due to its lower power output, a low-compression ratio Atkinson cycle engine cannot tow loads as well as a standard Otto-cycle engine of the same size. However, the presence of the hybrid powertrain would be expected to maintain towing utility for these vehicle types in all but the most severe operating extremes. Such extremes would include towing up very long duration grades (e.g., like in the Rocky Mountains) (i.e.,) or towing up a shorter but very steep grade (e.g., Pike's Peak)). Under these extreme towing conditions, the battery on a hybrid powertrain would eventually cease to provide sufficient supplemental power and the vehicle would be left with the engine doing all the work. A loss in utility would result (note that the loss in utility should not result in breakdown or safety concerns, but rather loss in top speed and/or acceleration capability). Importantly, those towing situations involving driving outside mountainous regions would not be affected.

The second possible exception to our attempt at maintaining utility is the electric vehicle range. We have built electric vehicle packages with ranges of 75, 100 and 200 miles. Clearly these vehicles would not provide the same utility as a gasoline vehicle which can be refueled very quickly and, therefore, has unlimited range (effectively). However, from an acceleration performance standpoint, the utility would be equal to if not perhaps better than the gasoline vehicle. We believe that buyers of electric vehicles in the MYs 2021-2025 timeframe will be purchasing the vehicles with a full understanding of the range limitations and will use their vehicles accordingly. As such, we believe that the buyers of EVs will experience no loss of expected utility.

[G] This towing/non towing distinction is not an issue for non-HEVs, EPA maintains whatever towing capability existed in the baseline when adding/substituting technology.

To prepare inputs for the OMEGA model, EPA builds "master-sets" of technology packages.[H] The master-set of packages for each vehicle type are meant to reflect both appropriate groupings of technologies (e.g., we do not apply turbochargers unless an engine has dual overhead cams, some degree of downsizing, direct injection and dual cam phasing) and limitations associated with penetration caps (see 2012 FRM joint TSD 3.5 and the brief discussion in Section 5.3.3). We then filter that list by determining which packages provide the most cost effective groups of technologies within each vehicle type—those that provide the best trade-off of costs versus CO_2 reduction improvements. This is done by ranking those groupings based on the Technology Application Ranking Factor (TARF). The TARF is the factor used by the OMEGA model to rank packages and determine which are the most cost effective to apply. The TARF is calculated as the net incremental cost (or savings) of a package per kilogram of CO_2 reduced by the package relative to the previous package. The net incremental cost is calculated as the incremental cost of the technology package less the incremental discounted fuel savings of the package over 5 years. The incremental CO_2 reduction is calculated as the incremental CO_2 /mile emission level of the package relative to the prior package multiplied by the lifetime miles travelled. More detail on the TARF can be found in the OMEGA model supporting documentation (see EPA-420-B-10-042). We also describe the TARF ranking process in more detail below. Grouping "reasonable technologies" simply means grouping those technologies that are complementary (e.g., turbocharging plus downsizing) and not grouping technologies that are not complementary (e.g., dual cam phasing and coupled cam phasing).

To generate the master-set of packages for each of the vehicle types, EPA has built packages in a step-wise fashion looking first at "simpler" conventional gasoline and vehicle technologies, then more advanced gasoline technologies such as turbocharged (with varying levels of boost) and downsized engines with gasoline direct injection and then hybrid and other electrified vehicle technologies. This was done by assuming that auto makers would first concentrate efforts on conventional gasoline engine and transmission technologies paired with some level of mass reduction to improve CO_2 emission performance. Mass reduction varied from no mass reduction up to 20 percent as the maximum considered in this analysis.[I]

Once the conventional gasoline engine and transmission technologies have been fully implemented, we expect that auto makers would apply more complex (and costly) technologies such as turbocharged and downsized gasoline engines and/or converting conventional gasoline engines to advanced diesel engines in the next redesign cycle. Auto makers may also move to hybridization, both mild and strong hybrids. For this analysis, we have built all of our mild

---

[H] In fact, we first build a package list of packages for each model for each model year for which we run OMEGA because penetration caps result in different technologies being available. From those, we build Master-sets for each relevant model year and emission standard combination since costs change over time resulting in different costs every year.

[I] Importantly, the mass reduction associated for each of the 19 vehicle types was based on the vehicle-type sales weighted average curb weight. Although considerations of vehicle safety are an important part of EPA's consideration in establishing the standards, note that allowable weight reductions giving consideration to safety is not part of the package building process so we have built packages for the full range of 0-20% weight reduction considered in this analysis. Weight consideration for safety is handled within OMEGA as described in Chapter 8 of this Draft TAR.

hybrid packages using the newly emerging 48 Volt technology. We have built two types of strong hybrid packages for this analysis, consistent with the 2012 FRM, as was described above.

Lastly, for some vehicle types (i.e., the non-Truck vehicle types), we anticipate that auto makers would move to more advanced electrification in the form of both plug-in hybrid (PHEV, sometimes referred to as range extended electric vehicles (REEV)) and full battery electric vehicles (BEV).[J]

Importantly, the HEV, PHEV and BEV (called collectively P/H/EV) packages here take into consideration the impact of the weight of the electrified components, primarily the battery packs. Because these battery packs can be quite heavy, if one removes 20 percent of the mass from a gasoline vehicle but then converts it to an electric vehicle, the resultant net weight reduction will be less than 20 percent. We discuss this in more below where we provide additional discussion regarding the P/H/EV packages.

The result of this package building process is a set of "Package List" files, one for MY2021 and one for MY2025. These package list files provide a description of each package, a unique package number for that package which follows that package throughout the OMEGA process within a given model year, and details of each technology and associated codes within each package. The distinction being made here is that the package description may include dual cam phasing (DCP), but the package details might indicate DCP on a V6 engine for one package, and DCP on an I4 engine for another package in the same vehicle type since this second package includes turbocharging and downsizing. The package list files used as part of EPA's analysis are contained in the docket and on our website and the step-by-step process is detailed below.[K]

In building MY2021 packages, we proceed according to the following sequence of steps (note that underlined technologies are simply meant to guide the reader to differences between technologies included in packages; note also that the number of packages are unique to non-Truck vehicle types, slightly more HEV packages are built for Truck vehicle types since they are built with both TDS18 and TDS24 while non-Truck vehicle types are built with only Atkinson 1 engines; the final result is 9269 packages per non-Truck vehicle type and 9360 for each Truck vehicle type, or roughly 270,000 packages):

1) With 5 percent mass reduction:
    a) With TRX11 & again with TRX12 (2 packages):
        i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 1, passive aero, low drag brakes, variable valve timing
    b) With TRX11 & again with TRX12 (2 packages):
        i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 1, passive plus <u>active aero</u>, low drag brakes, variable valve timing

[J] In some OMEGA files, BEV is also referred to as EV.

[K] See our website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

c) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 2, electric power steering, lower rolling resistance tires level 1, passive plus active aero, low drag brakes, variable valve timing

d) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive aero, low drag brakes, variable valve timing

e) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

f) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 1, improved accessories level 2, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

g) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive aero, low drag brakes, variable valve timing

h) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 1, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

i) With TRX11 & again with TRX12 (2 packages):

   i) Low friction lubes, engine friction reduction level 2, improved accessories level 2, electric power steering, lower rolling resistance tires level 2, passive plus active aero, low drag brakes, variable valve timing

j) Steps 1.a through 1.i with cylinder deactivation (18 packages)

k) Steps 1.a through 1.i with gasoline direct injection (18 packages)

l) Steps 1a. through 1.i with cylinder deactivation and gasoline direct injection (18 packages)

m) Steps 1.a through 1.l with stop-start (72 packages)

n) Steps 1.a through 1.m with secondary axle disconnect (144 packages)

o) Any package in Steps 1.a through 1.m that includes gasoline direct injection, add Atkinson-2 (144 packages)

p) Step 1.o, add cooled EGR (144 packages)

q) Any package in Steps 1.a through 1.m that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 18-bar (144 packages)

r) Any package in Steps 1.a through 1.m that includes gasoline direct injection, replace cylinder deactivation with discrete variable valve lift and add turbo-downsize 24-bar plus cooled EGR (144 packages)

s) Any package in Steps 1.a through 1.m that includes gasoline direct injection, add Miller-cycle plus cooled EGR (144 packages)

t) Step 1.a through 1.s with TRX21 & again with TRX22 (1008 packages)

u) Any packages with improved accessories level 2, add mild HEV 48V (336 packages)

v) Any packages with gasoline direct injection, engine friction reduction level 2 and lower rolling resistance tires level 2, add advanced diesel (24 packages)

2) With 10 percent mass reduction

   a) Repeat Step 1 (2376 packages)

   b) Step 2.a packages with improved accessories level 1 and no advanced diesel, add strong HEV (48 packages)

3) With 15 percent mass reduction

   a) Repeat Step 2 (2424 packages)

4) With 20 percent mass reduction (not done for "Truck" vehicle types)

   a) Build PHEV20 & PHEV40 (REEV20 & REEV40) (2 packages)

   b) Build EV75, EV100, EV200 (3 packages)

5) For off-cycle levels 1 and 2

   a) Any Step 1 through 3 packages with active aero, lower rolling resistance tires level 2, improved accessories level 2 and TRX21

      i) Add off-cycle level 1 (OC1) (510 packages)

   b) Any Step 1 through 3 packages with active aero, lower rolling resistance tires level 2, improved accessories level 2 and TRX22

      i) Add off-cycle level 1 (OC1) (510 packages)

   c) Any package with off-cycle level 1, remove off-cycle 1 and add off-cycle level 2 (OC2) (1020 packages)

In building MY2025 packages, we proceed according to a very similar sequence as outlined above with the exception that the presence of fewer penetration caps in MY2025 means less iteration on first level technologies resulting in fewer sub-steps within Step 1 and, as a result, fewer packages per vehicle type.

The package lists are then sent through EPA's TEB-CEB "Machine" which is the tool in the OMEGA process that brings together technology costs and technology effectiveness (via the Lumped Parameter Model) to determine package level costs and effectiveness. The TEB-CEB Machine calculates the Technology Effectiveness Basis and the Cost Effectiveness Basis of each package. With package level costs and effectiveness, we can then use the OMEGA Master-set generator tool to generate a Master-set of packages. The Master-set of packages adds to the package cost and effectiveness values the 5-year discounted fuel savings and lifetime CO_2 reductions for each package.[L] These additional metrics allow for calculation of a TARF for each unique package contained in the applicable package list. Importantly, in building packages and the Master-sets of packages, we have not yet considered the baseline fleet beyond the sales-weighted metrics of each of the 29 vehicle types. Instead, we have considered only appropriate groupings of technologies into packages and built packages and Master-sets based on the 29 vehicle types and the sales-weighted attributes of those vehicle types (e.g., CO_2 and curb weight).

5.3.3 Master-set Ranking and the Technology Input File

This master-set of packages is then ranked by TARF within vehicle type for each Master-set of packages necessary to represent the reference case and the control case. In this analysis, this requires 4 Master-sets: Reference case in MY2021, Reference case in MY2025, Control case in MY2021 and Control case in MY2025. However, we can use the same Master-set for both the Reference case in MY2021 and the Control case in MY2021 since the same set of costs apply. The end result being a necessary set of 3 Master-sets for a given OMEGA run. Should any effectiveness or cost value, synergy factor, fuel price, etc., be changed, a different Master-set or group of Master-sets would be required.

The ranking process is handled by the OMEGA pre-processing Ranking Algorithm (contained in the docket and on our website) which calculates the TARF of each package relative to the sales-weighted representative package within a given vehicle type. The package with the best TARF is selected as OMEGA package #1 for that vehicle type. The remaining packages for the given vehicle type are then ranked again by TARF, this time relative to OMEGA package #1. The best package is selected as OMEGA package #2, etc.

An important consideration in the ranking process is the penetration caps which cannot be exceeded to ensure that the packages chosen by the ranking do not result in exceedance of the caps. As such, if package #2 contains a technology, for example TRX21, but the penetration cap for TRX21 is, say 60 percent, then only 60 percent of the population of vehicles in the given vehicle type would be allowed to migrate to package #2 with the remaining 40 percent left in package #1. We had a detailed discussion of penetration caps in Section 3.5 of the final joint TSD in support of the 2012 FRM.[4] For this analysis, we have used the same penetration caps as

[L] These metrics are calculated using the sales weighted CO_2 level of all vehicles mapped into each specific vehicle type.

presented there with the exception of adding a new penetration cap for the Atkinson-2 technology, which was not considered in the 2012 FRM. The Atkinson-2 penetration cap used in this analysis is the same as that used in the Draft TAR. For the mild HEV 48V technology, we have used the same penetration cap as used for the mild HEV technology described in the 2012 FRM and as used in the Draft TAR. For the new Miller cycle technology, we have used the 24-bar turbocharging penetration caps used in the 2012 FRM and the Draft TAR. The penetration caps used in this analysis are shown in the table below. New for this analysis are penetration caps for off-cycle level 1 and 2 (OC1 and OC2). For those, we have not applied any caps.

Table 5.2 Penetration Caps used in the OMEGA Central Analysis Runs

Tech code	Tech	2021	2025
Aero 1	Aero – passive	100%	100%
Aero 2	Aero – passive with active	80%	100%
ATK2	Atkinson-2	80%	100%
CCC	Camshaft configuration changes without downsizing	100%	100%
CCP	Coupled cam phasing	100%	100%
CVVL	Continuous variable valve lift	100%	100%
DCP	Dual cam phasing	100%	100%
Deac	Cylinder deactivation	100%	100%
DSL-Adv	Advanced diesel	30%	42%
DVVL	Discrete variable valve lift	100%	100%
EFR1	Engine friction reduction level 1	100%	100%
EFR2	Engine friction reduction level 2	60%	100%
EGR	Cooled exhaust gas recirculation	30%	75%
EPS	Electric power steering	100%	100%
EV75	Full battery electric vehicle 75 mile range	5%	8%
EV100	Full battery electric vehicle 100 mile range	5%	8%
EV200	Full battery electric vehicle 200 mile range	5%	8%
DI	Gasoline direct injection	100%	100%
IACC1	Improved accessories level 1	100%	100%
IACC2	Improved accessories level 2	80%	100%
LDB	Low drag brakes	100%	100%
LRRT1	Lower rolling resistance tires level 1	100%	100%
LRRT2	Lower rolling resistance tires level 2	75%	100%
LUB	Engine changes to accommodate low friction lubes	100%	100%
MHEV48V	Mild hybrid 48V	50%	80%
P2 or HEV	Strong hybrid	30%	50%
REEV20	Range extended or plug-in electric vehicle 20 mile range	8%	11%
REEV40	Range extended or plug-in electric vehicle 40 mile range	8%	11%
SAX	Secondary axle disconnect	100%	100%
Stop-start	Stop-start without electrification	100%	100%
TDS18	Turbocharging with downsizing 18-bar	100%	100%
TDS24	Turbocharging with downsizing 24-bar	30%	75%
TRX11	Transmission – step 1 or current generation	100%	100%
TRX12	TRX11 with improved efficiency	30%	100%
TRX21	Transmission – step 2 or TRX11 but with additional gear-ratio spread	80%	100%
TRX22	TRX21 with improved efficiency	30%	100%
TURBM	Miller cycle or ATK2 with turbocharging	30%	75%
WR10	Weight reduction of 10% from EPA's "null"	100%	100%
WR15	Weight reduction of 15% from EPA's "null"	100%	100%
WR20	Weight reduction of 20% from EPA's "null"	0%	100%
OC1	Off-cycle level 1	100%	100%
OC2	Off-cycle level 2	100%	100%

Also tracked are the credits available to the package which are also included in this ranking process.[M] The table below presents 2015 baseline data used in the TARF ranking process.

Table 5.3 Lifetime VMT & Baseline CO_2 used for the TARF Ranking Process

Vehicle Type	Description	Curb Weight Class	ALPHA Class	Example Models	C/T	MY2021 Lifetime VMT	MY2025 Lifetime VMT	Base CO_2 (g/mi)
1	I4 DOHC	1	LPW_LRL	Sentra, Corolla	C	184,789	189,264	201.4
2	I4 DOHC	1	MPW_LRL	Dart, Focus	C			241.2
3	I4 DOHC	2	MPW_LRL	Altima, Camry	C			232.7
4	I4 DOHC	2	LPW_HRL	Rogue, Patriot	C			249.3
5	I4 DOHC	3	MPW_LRL	Malibu, 200	C			242.7
6	I4 DOHC	3	LPW_HRL	Forester, Cherokee	C			247.8
7	I4 DOHC	4	LPW_HRL	Outback, Equinox	T	214,994	220,200	264.3
8	I4 DOHC	6	Truck	Colorado, Tacoma	T			321.9
9	V6 OHV	6	Truck	Silverado, Sierra	T			354.2
10	V6 SOHC	3	HPW	RDX, TLX	C	184,789	189,264	288.9
11	V6 SOHC	4	MPW_HRL	Odyssey	T	214,994	220,200	321.2
12	V6 DOHC	1	LPW_LRL	Turbo Cruze, Turbo Focus	C	184,789	189,264	223.2
13	V6 DOHC	2	MPW_LRL	Turbo Fiesta, Turbo Jetta	C			243.6
14	V6 DOHC	2	LPW_LRL	Turbo Encore, Diesel Jetta	C			235.9
15	V6 DOHC	3	HPW	E350, Impala, Q50	C			276.6
16	V6 DOHC	3	MPW_LRL	IS250	C			272.9
17	V6 DOHC	3	LPW_HRL	Transit	C			265.3
18	V6 DOHC	4	HPW	Charger	C			317.5
19	V6 DOHC	4	MPW_HRL	Pathfinder, Journey	T	214,994	220,200	291.3
20	V6 DOHC	5	HPW	Camaro	T			336.2
21	V6 DOHC	5	MPW_HRL	Grand Cherokee	T			349.1
22	V6 DOHC	6	Truck	Tacoma, Frontier	T			366.1
23	V8 OHV	5	HPW	Charger	T			392.0
24	V8 OHV	5	MPW_HRL	Tahoe, Suburban	T			379.7
25	V8 OHV	6	Truck	Silverado, Sierra	T			383.7
26	V8 DOHC	4	HPW	Mustang, SL550	C	184,789	189,264	334.7
27	V8 DOHC	5	HPW	BX460	T	214,994	220,200	383.0
28	V8 DOHC	5	MPW_HRL	Tundra, F150	T			377.2
29	V8 DOHC	6	Truck	Turbo F150, Diesel Ram	T			394.7

Once a Master-set is ranked, the result is a Ranked-set of packages with a maximum of 50 packages for each vehicle type. This Ranked-set of packages is used to generate the Technology input file for the OMEGA core model and to generate the "Scenario packages" to be applied to vehicles within each vehicle type. In the Technology input file, the package progression, or "flow" of packages is included. The package progression is key because OMEGA evaluates each package in a one-by-one, or linear progression. The packages must be ordered correctly so that no single package will prevent the evaluation of the other packages. For example, if we

[M] We have included credits for aerodynamic treatments level 2, 12V stop-start, mild HEV and strong HEV.

simply listed packages according to increasing effectiveness, there could well be a situation where an HEV with higher effectiveness and a better TARF than a turbocharged and downsized package with a poor TARF could never be chosen because the turbocharged and downsized package, having a poor TARF, would never get chosen and would effectively block the HEV from consideration. For that reason, it is important to first rank by TARF so that the proper package progression can be determined. In other words, packages do not necessarily flow from a given package to the next package listed. Because of the penetration caps, a package listed as, for example, step 8 might actually come from step 5 rather than from step 7. As such, within OMEGA, the incremental cost for step 8 would be the cost for step 8 less the cost for step 5 and similar for the effectiveness values. All of the Ranked-sets of packages and the Technology input files are contained in the docket and at our website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

5.3.4 Applying Ranked-sets of Packages to the Projected Fleet

As noted above, when we apply a package of technologies to an individual vehicle model in the baseline fleet, we must first determine which package of technologies are already present on the individual vehicle model. From this information, we can determine the effectiveness and cost of the individual vehicle model in the baseline fleet relative to the "null" package that defines the vehicle type. Once we have that, we can determine the incremental increase in effectiveness and cost for each individual vehicle model in the baseline fleet once it has added the package of interest. This process is known as the TEB-CEB process, which is short for Technology Effectiveness Basis - Cost Effectiveness Basis. This process allows us to accurately reflect the level of technology already in the 2015 baseline fleet as well as the level of technology expected in the MYs 2021-2025 reference case (i.e., the fleet as it is expected to exist as a result of the MY 2021 standards).

The TEB-CEB Machine is again used, along with a set of Scenario packages, to generate the actual TEB and CEB values for each package as it is applied to each individual model within the analysis fleet. These TEB and CEB values, along with the off-cycle effectiveness (OEB) values are then used in the Market input file and serve as one of the primary inputs to the OMEGA core algorithms.

The TEB-CEB Machine's process when applying Ranked-set packages to actual vehicles can be broken down into four steps. The first step in the process is to break down the available GHG control technologies into five groups: 1) engine-related, 2) transmission-related, 3) hybridization, 4) weight reduction and 5) other. Within each group we gave each individual technology a ranking which generally followed the degree of complexity, cost and effectiveness of the technologies within each group. More specifically, the ranking is based on the premise that a technology on a baseline vehicle with a lower ranking would be replaced by one with a higher ranking which was contained in one of the technology packages which we included in our OMEGA modeling. The corollary of this premise is that a technology on a baseline vehicle with a higher ranking would be not be replaced by one with an equal or lower ranking which was contained in one of the technology packages which we chose to include in our OMEGA modeling. This ranking scheme can be seen in Visual Basic Macro contained within the TEB-CEB Machine which is in available in the docket and on our website at https://www.epa.gov/regulations-emissions-vehicles-and-engines/optimization-model-reducing-emissions-greenhouse-gases.

In the second step of the TEB-CEB process, these technology group rankings are used to estimate the complete list of technologies which would be present on each vehicle after the application of a technology package. In other words, this step indicates the specific technology on each vehicle after a package has been applied to it. The Machine then uses EPA's lumped parameter model to estimate the total percentage CO_2 emission reduction associated with the technology present on the baseline vehicle (termed package 0), as well as the total percentage reduction after application of each package. The Machine uses this approach to determine the total cost of all of the technology present on the baseline vehicle and after the application of each applicable technology package.

The third step in this process is to account for the degree to which each technology package's incremental effectiveness and incremental cost is affected by the technology already present on the baseline vehicle. For this analysis, we also account for the credit values using a factor termed "Other effectiveness basis (OEB).

As described above, technology packages are applied to groups of vehicles which generally represent a single vehicle platform and which are equipped with a single engine size (e.g., compact cars with four cylinder engines produced by Ford). Thus, the fourth step is to combine the fractions of the CEB and TEB of each technology package already present on the individual baseline vehicle models for each vehicle grouping. For cost, percentages of each package already present are combined using a simple sales-weighting procedure, since the cost of each package is the same for each vehicle in a grouping. For effectiveness, the individual percentages are combined by weighting them by both sales and base CO_2 emission level. This appropriately weights vehicle models with either higher sales or CO_2 emissions within a grouping. Once again, this process prevents the model from adding technology which is already present on vehicles, and thus ensures that the model does not double count technology effectiveness and cost associated with complying with the modeled standards.

The other effectiveness basis (OEB) was designed to appropriately account for credit differences between technologies actually on the vehicle and technology packages applied through the technology input file. As an example, if a baseline vehicle includes start stop technology, and the applied package does not, the model needs to account for this different in off-cycle credit. The OEB is an absolute credit value and is used directly in the model's compliance calculations.

5.3.5 New to OMEGA since the Draft TAR

Based on input from public comments and other information that became available to us, we made certain changes to what we term the "OMEGA Suite" of tools used in generating a full Benefit-Cost Analysis. Those changes are listed below and are detailed throughout this TSD:

- The baseline fleet was updated from a basis in MY2014 to MY2015
- Future vehicle sales projections were updated based on AEO2016 sales projections.
- The ZEV program sales were updated based on the updates mentioned above.
- All fuel prices used throughout the OMEGA Suite now use AEO2016 fuel prices.

- All monetized values (technology costs, maintenance costs, SCC and non-GHG cost/ton values, etc.) have been updated to 2015 dollars for consistency with AEO2016 fuel price estimates.
- Vehicle mileage accumulation rates and survival rates were updated based on AEO 2016 projections.
- Baseline levels of mass reduction were updated for the new baseline fleet.
- Baseline levels of passive and active aero technologies were updated resulting in more use of those technologies in the MY2015 baseline than in the Draft TAR fleet.
- Baseline levels of lower rolling resistance tires level 1 and 2 were updated resulting in more use of those technologies in the MY2015 baseline than in the Draft TAR fleet.
- Corrected an internal coding error in the mass reduction penalty determination associated with the added weight of the battery on strong HEVs which, in the Draft TAR, was erroneously 0 percent on all strong HEVs. Similarly, corrected an error in the mass reduction tracking where mass reduction penalties are involved (i.e., mild and strong HEVs, PHEVs and full EVs); this resulted in some WRtech/WRpen/WRnet values being confused.
- Updated the methodology used for calculating allowed mass reduction levels in light of applicable mass reduction technology penetration caps. Those allowed levels of mass reduction are now based on "null" curb weight rather than simply "baseline" curb weight as was done in the Draft TAR. This is more consistent with the basis for the penetration caps which also are based on null curb weight. In turn, we also updated the methodology for applying maximum mass reduction levels as part of the safety analysis.
- All full BEV and PHEV vehicles are placed on unique platforms rather than being part of an internal combustion engine (ICE) platform. This is true of BEV/PHEV in the baseline and those created as part of the ZEV program fleet, which results in many more platforms than in the Draft TAR. This was done to allow for accounting of upstream emissions for BEV/PHEV in OMEGA.
    - This also required an update to the Technology Effectiveness Basis (TEB) calculation for full EVs. In all prior versions of OMEGA, the TEB for a full BEV was always 0 gCO2/mi. The TEB is now calculated as equivalent to the baseline vehicle's indicated CO2 level which is user controlled. In OMEGA for this analysis, when considering upstream emissions associated with electricity consumption, we have entered the upstream emissions value as the baseline CO2 level. That way, the TEB reflects upstream CO2 emissions and the manufacturer's compliance determination, likewise, reflects those upstream emissions.
    - These upstream emissions are then post-processed via a new post-processing summary generating tool to correctly track tailpipe CO2 versus upstream (or grid) CO2.

  - The OMEGA Market file now shows grid CO2 for BEV/PHEV (in a formerly unused column called "Towing Capacity" and codes them as fueled by electricity despite PHEVs being fueled also by gasoline. The electricity fuel code serves only as a trigger for the TEB-CEB process to use the baseline values at every package step.

- Correction made to the treatment of stop-start technology on baseline vehicles which, in the Draft TAR, was mistakenly ignored.
- Correction made to the effectiveness calculation of Miller cycle engines such that the Atkinson 2 portion is no longer double counted.
- Correction made to the reporting of included technologies in OMEGA "tech code strings" such that BEV and PHEV tech codes are no longer included simultaneously.
- Updated vehicle classifications away from categories such as "small car" and "large MPV and toward a power-to-weight and road-load determination. Similarly, updated cost classifications away from categories such as "small car" and "large MPV" and toward a curb weight classification system since curb weight better reflects applicable costs (e.g., mass reduction costs, battery costs).
- Application of BEV and/or PHEV technology is no longer determined based on a loose "towing" versus "non-towing" determination. Instead, BEV and PHEV technologies are now allowed on most vehicles with the sole exception of pickup trucks. As a result, many more MPV-type vehicles (minivans, SUVs, cross-over utilities) are now open to electrification whereas those technologies were not considered for those vehicles in the Draft TAR.
- A correction was made to the calculation of indirect costs on some transmission technologies resulting in slightly lower TRX costs in this analysis (see discussion in Section 2.3.4.2.4 of this TSD).
- Numerous updated effectiveness values including new ALPHA vehicle determinations (i.e., termed the ALPHA "exemplar" vehicles). These changes are detailed in Chapter 2 of this TSD.
- The OMEGA ICBT includes updated MOVES runs (taking into account AEO2016 projections) to generate new emission factors used on inputs to the OMEGA ICBT.
- The OMEGA ICBT now corrects an error which applied AEO reference fuel prices in calculating monetized fuel savings, even in the AEO high and low fuel price cases.
- The OMEGA ICBT was updated to include payback calculations in the case where loan purchases were used rather than simply cash purchases.
- The OMEGA ICBT payback analysis now applies vehicle survival rates to insurance costs and loan payback costs. This places those costs on the same basis as the fuel savings and maintenance costs which have always included vehicle survival rates.

REFERENCES

[1] EPA-420-R-12-024, August 2012.
[2] EPA-420-R-09-016, September 2009. (Docket No. EPA-HQ-OAR-2010-0799-1135).
[3] EPA-420-R-12-901, August 2012.
[4] EPA-420-R-12-901, August 2012.

Table of Contents

Table of Figures

Table of Tables

Appendix A EPA Response to the Alliance of Automobile Manufacturers' Contractor Reports Titled "Final Report for Technology Effectiveness [Phases 1 and 2]"

In its comments on EPA's technology, assessment and modeling processes in the Draft TAR, the Alliance of Automobile Manufacturers states that the EPA projections of potential vehicle and fleet effectiveness do not match "third-party modeling outputs."[1] This claim (as well as others scattered throughout the Alliance's comments) relies heavily on conclusions drawn in a pair of non-peer-reviewed reports produced by The Alliance's contractor, Novation Analytics. These reports provide some speculative conclusions, based on simple technology models, about future vehicle effectiveness at both the fleet[2] and vehicle level.[3]

Copies of the reports were provided by the Alliance as attachments to its comments. Pointing to the Novation fleet-level report, the Alliance draws the conclusion that "MY2021 and MY2025 targets cannot be met with the suite of technologies at the deployment rates projected by the agencies in the 2012 FRM"[4] and that "automakers will need to apply additional and costlier technologies than were initially predicted to meet the projected MY2021 and MY2025 targets."[5]

The EPA disagrees with the conclusions drawn by the Alliance. These reports by the Alliance's contractor are riddled with technical flaws, unsound initial assumptions, and unsubstantiated claims that substantially skew the final conclusions. Moreover, the errors in the reports tend to systematically under-predict technology effectiveness and over-predict the cost and complexity of the technology required to meet the standards. This opinion of Novation's work is shared by Dave Cooke of the Union of Concerned Scientists, who outlines just a few of the "fundamental mistakes that ensure that the report comes out the way the automakers envisioned."[6]

A.1 Constraints on Technology Combinations and Technological Innovation

The most basic of the "fundamental mistakes" in the report, and one that directly affects all of the conclusions drawn by the Alliance on projected technology effectiveness, is the contention that all possible technology available in 2025 can be represented by technology already contained in the MY2014 baseline fleet.

Novation's report assumes from the outset that "the MY2014 fleet... includes the majority of the spark ignition technology pathways utilized in the agency assumptions" and, therefore, "it is not likely that the sales-weighted fleet performance [in MYs 2017-2025] will exceed the current boundaries established by the best in class vehicles utilizing many of the technologies listed above."[7] This unsubstantiated initial assumption effectively limits powertrain efficiency in 2025 to small incremental improvements over that which is available today.

The EPA does not agree that MY2014 powertrain efficiency can define the maximum achievable efficiency. Although it may be correct that "the majority of the spark ignition technology" considered in the FRM exists in the present-day fleet (thus proving the viability of individual technologies), the powertrain components incorporating these sub-technologies exist in combinations and within packages that are designed to meet current standards, not future standards.

The LD GHG standards are phased in, with increasing stringency from year to year. These standards do not require manufacturers to meet MY2025 standards in MY2014, and the EPA anticipates that, for cost reasons, manufacturers will generally seek to minimize over-compliance beyond the credit carryforward duration. Thus, the combinations of, and packages incorporating, advanced technology that exist in the MY2014 fleet should be expected to be only as effective as necessary to meet (or slightly over-comply with[A,8]) MY2014 standards, but nowhere near the effectiveness level required by 2025 standards. In later years, manufacturers have the ability to incorporate additional technologies into their vehicles, and to recalibrate or refine existing technologies, thereby increasing powertrain efficiency accordingly.

In later years, manufacturers also have the option to combine sub-technologies into packages which are more effective than those that exist within the market today. EPA's projections of effectiveness through MY2025 include technology packages that are achievable and cost-effective, but do not exist in the fleet in MY2014 - for example, a 24 bar turbocharged downsized engine with cooled EGR, or a high compression ratio Atkinson cycle engine with cylinder deactivation and cooled EGR. The methodology in the Novation report does not allow for the recombination of technologies represented by these packages, and thus severely and unduly limits potential effectiveness increases obtainable by MY2025.

In fact, Novation's initial assumption on powertrain efficiency is equivalent to the argument that because manufacturers are not substantially over-complying with current standards, they could not possibly comply with more stringent future standards. This argument is unreasonable on its face, and relies on the logical fallacy of circular reasoning, where the conclusion of an argument is included within the initial assumptions.

A.2 Novation's Simplistic Methodology and Lack of Rigor

This fundamental flaw in the report's assumptions and conclusions results from the lack of rigor in their "top-down" methodology (as pointed out by other organizations[9]). When correctly implemented, "top-down and bottom-up approaches should converge to the same result"[10] (as the Novation report states). However, the choice to rely on vehicles, technologies, and technology packages that exist in the MY2014 fleet produce a consistent bias that underestimates potential technology effectiveness.

The Novation report oversimplifies the technologies, and the relationships among them, that exist in the current fleet. The methodology within the report is to survey the MY2014 fleet, grouping vehicles into broad "technology bundles" according to their powertrain. Within each bundle, the underlying technology was assumed to be identical, and any differences among powertrains attributed solely to "learning and implementation improvements."[11] For example, one "bundle" is defined as an SI naturally aspirated engine coupled with a non-high ratio spread transmission, without stop-start. This bundle presumably includes vehicles with Atkinson cycle engines or cylinder deactivation, yet ascribes any efficiency gains due to the advanced technology to "learning."

The report then uses the statistical distribution of efficiency across all powertrains in each "bundle" to estimate powertrain efficiency out to 2025, with average future efficiency set equal

[A] In MY2014, overall industry compliance was 13 grams/mile better than required by the 2014 GHG emissions standards. This is consistent with the level of over-compliance in MYs 2012 and 2013.

to the current 75th or 90th percentile. The simplistic assumption that "learning" is the source of efficiency differences within each technology bundle obscures the actual effect of hardware and technology differences among individual powertrains. Moreover, the assumption automatically eliminates any consideration of the effect of recombining sub-technologies, as a "bottom-up" methodology would.

The lack of rigor of the approach taken in the Novation report is immediately obvious if individual components or sub-technologies are examined, rather than the entire powertrain as an indissoluble package. At the highest level, powertrains are comprised of engines and transmissions. Even in the MY2014 fleet, there are few if any 2014 best-in-class engines which are packaged with 2014 best-in-class transmissions; and so even the 2014 best-in-class powertrain underperforms what is clearly possible with off-the-shelf technology. At finer levels of technology packaging, best-in-class engines and transmissions do not have all available technology packaged on them.

In addition to constraining future powertrain packages to those technology combinations existing within the MY2014 fleet, as stated above, the Novation report assumes that no innovation will occur – no new technology will be implemented – in the eleven years until MY2025. Although "the majority" of technologies discussed in the FRM exist in the MY2014 fleet, there are some that do not, but can be reasonably expected to be phased in before 2025. As a single example, the Alliance in their comments acknowledges that "FCA US LLC (FCA) recently introduced an upgraded 8-speed rear-wheel drive transmission"[12] which incorporated some elements of an advanced high efficiency gearbox (HEG2), improving upon the MY2014 best-in-class eight-speed transmission and reducing unadjusted combined fuel consumption by approximately 0.8 percent. Moreover, the artificial limitation on innovation imposed in the Novation report completely discounts the effect of further innovation in the industry (such as, for example, Nissan's production-ready variable compression ratio engine, available in 2018[13]), which may provide further cost-effective reductions in GHG emissions and fuel consumption. The Novation report assumes that new technologies like these (and others already announced by manufacturers to be utilized on future products), along with the fuel consumption benefits derived from them, would be impossible to incorporate in the future fleet.

In the few cases where the Novation report explicitly addresses technology not contained in the MY2014 fleet, they invent arbitrary "proxies" to estimate powertrain efficiency. For example, the Novation report arbitrarily claims that powertrains incorporating "the current compression ignition (24-29 bar maximum BMEP diesel) can be used as a representative proxy" for a 27 bar SI engine powertrain.[14] No technical rationale for this choice is provided, and the report again relies on circular reasoning by using the argument that "it is unlikely even an advanced SI package will exceed the current CI efficiency boundary" to support the choice of using current CI powertrain efficiencies as a proxy for 27 bar SI engine powertrain efficiencies.

A.3 Omission of Vehicle Load and Technology Penetration Rate Changes

In addition to consistently underestimating the potential effectiveness of advanced powertrain technology, the Novation report compounds the errors by blindly following technology projections in the 2012 FRM in circumstances where it is clearly not appropriate to do so.

The 2012 FRM projections are based on estimates of the most cost-effective technology packages necessary to reach a sales-weighted target CO_2 emission level, accounting for cost and effectiveness of powertrain technologies, cost and effectiveness of vehicle load reduction technologies (mass, aerodynamic resistance, and rolling resistance), applied credits, and sales mix of individual manufacturers. Altering the effectiveness of technologies, even as a sensitivity study, by definition changes the associated cost-effectiveness. In an alternative world where powertrain technology cost-effectiveness is different, the EPA would revise its modeling and likely project a different mix of technologies in future fleets, as the cost effectiveness of each technology would likely change in comparison to the others.

The Novation report attempts to quantify the technology penetration mix in an alternate world where technology effectiveness is lower. However, in doing so, the Novation report inappropriately maintains the original FRM assumptions on the non-powertrain portions of the fleet projection while altering the powertrain assumptions. The result is that, even if the powertrain efficiency estimation within the report were properly done, the alternate technology mix in the future fleet is costlier than a reasonable methodology would predict, as the methodology within the Novation report assesses neither road load reduction technologies, changes in credits, nor cost.

A.4 Arbitrary and Restrictive Assumptions and Constraints

In their comments on the Draft TAR, the Alliance of Automobile Manufacturers also discuss "modeling process issues" that they claim to be "the key source of error in technology benefit estimates."[15] To support this claim, the Alliance refers to statements in the vehicle-level report from their contractors, Novation Analytics,[16] where Novation attempts to justify the conclusions contained in their fleet-level report by examining powertrain efficiency on a vehicle basis.

The vehicle-level report adds to the list of fundamental mistakes contained in the earlier report by the same contractor. In addition to arbitrarily limiting technological progress to combinations existing in the fleet in MY2014, this Novation report likewise depends throughout on arbitrary assumptions and constraints which are largely unexplained, lacking in technical foundation, or unsupported by scientific rationale.

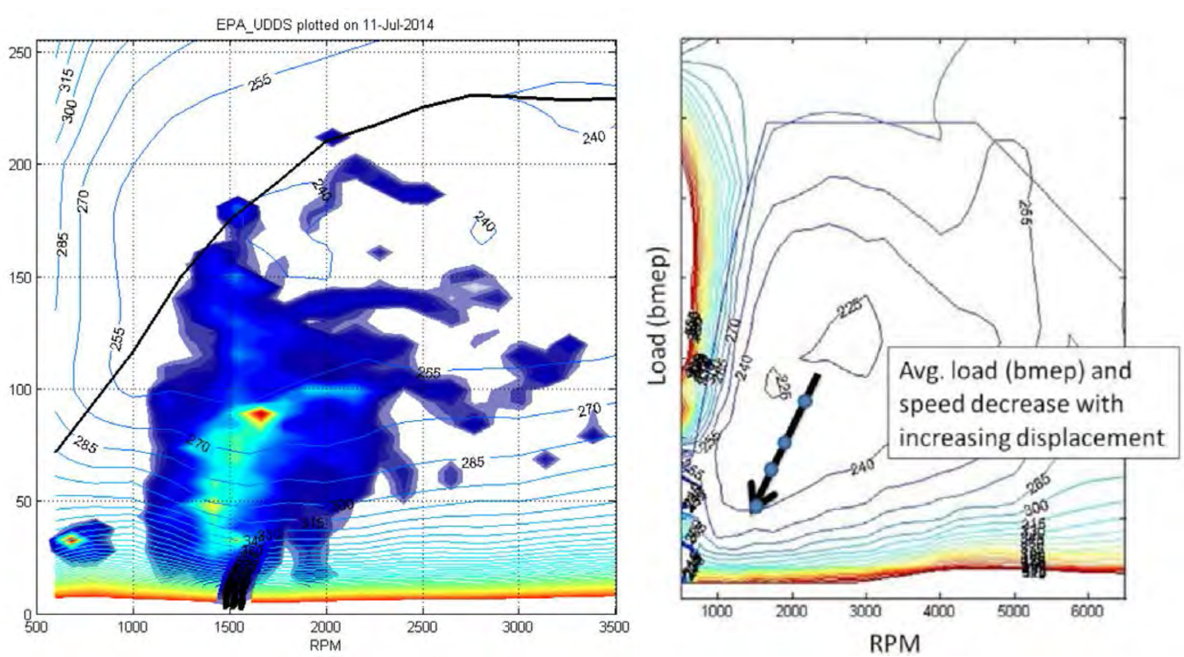
In particular, many of the conclusions in the Novation report, which are repeated by the Alliance in their comments, are based on the calculation of powertrain efficiency and the application of what Novation claim to be "basic, and very liberal, plausibility checks"[17] on the limit of powertrain efficiency. There are indeed fundamental limits on efficiency, but recognizing that efficiency is limited is a thermodynamic truism,[18] and a principle that was never in question. In fact, calculation of powertrain efficiency can serve as a gross QC check on estimated technology effectiveness by quickly identifying the highest efficiency packages for further review (as shown in Appendix B).

However, although examining powertrain efficiency can be useful, the Novation report further attempts to establish hard numerical limits on this efficiency, and it is here that overly restrictive assumptions creep in. Although the report claims to use "optimistic assumptions of technology effectiveness potential and ample margin for uncertainty, so that the tests would allow all but the most implausible results to pass,"[19] the assumptions used to estimate plausibility limits are unduly conservative and not at all optimistic. In fact, the Union of Concerned Scientists identifies at least one current production vehicle, a Honda Fit, which would be deemed implausible by the Novation report methodology.[20]

As one example, to determine the limit of on-cycle-to-peak engine efficiency ratio ("Plausibility Test 2"), the Novation report calculates the efficiency ratios for the FTP, HWFET, and combined cycles of three MY2013-2014 vehicles and selects the highest one. That efficiency ratio is increased by a small amount to account for decreased fuel consumption due to stop-start, decel fuel cutoff, and advanced transmissions based on "an independent [and uncited] analysis of modal data... conducted on seven current generation vehicles." [21] The final numbers, based on what appear to be seven to ten random vehicles from MY2013-2014, are presented as "very liberal plausibility checks" [22] for MY2025 powertrains, and any results which "exceed these ratios are judged to be implausible."[23]

This accounting process, if performed with care, could reasonably be expected to deliver a quick, low fidelity efficiency estimate for a particular technology package. However, the process is clearly inadequate as a bounding "plausibility test," and ignores substantial sources of effectiveness discussed in the 2012 FRM and 2016 Draft TAR. For example, as part of the explanation of this plausibility test, the Novation report reproduces a MY2013 Chevrolet Malibu GDI engine map, overlaid with the operational area for a UDDS cycle (see Figure 1.1(a)). The report correctly points out the gap between the engine operational area and the area of peak efficiency in this map as an explanation for why the on-cycle-to-peak engine efficiency ratio would be less than one.

In contrast, one substantial source of effectiveness in turbo downsized engines (compared to their naturally aspirated counterparts) is that the area of peak efficiency in the map is pushed to an area of lower speed and load (i.e., down and to the left), resulting in a much better match between peak efficiency and the operational area. This can be seen by comparing a 27-bar BMEP cooled EGR turbo GDI engine map (Figure 1.1(b), also reproduced in the Novation report), with the Malibu map in Figure 1.1(a).



(a) MY2013 Chevrolet Malibu 2.5L I4 GD (b) 27-bar BMEP cooled EGR turbo GDI

Figure 1.1 Two engine BSFC maps, reproduced in Technology Effectiveness – Phase II: Vehicle-Level Assessment and cited during the development of "Plausibility Test 2." The left-hand map is overlaid with areas of typical on-cycle engine operation. Original sources are given in the Novation report.[24]

The better match between engine operation and peak efficiency reduces CO_2 emissions, precisely by increasing the on-cycle-to-peak engine efficiency ratio. Since the Novation report develops a plausibility limit for on-cycle-to-peak engine efficiency ratio based on a few MY2013-2014 vehicles, no room is left for potential improvement in the efficiency matching; this is yet another example of the Novation report using an overly restrictive initial assumption to dismiss potential technological improvement.

The Alliance suggests in their comments that the EPA implement an additional level of QC check, beyond those detailed in the Draft TAR, based on the numerical limits given in the Novation report.[25] Although the EPA has used powertrain efficiency calculations as a QC tool (see Appendix B), the EPA believes the numerical limitations on efficiency suggested in the Novation report are not calculated in a robust and scientifically defendable way, and basing the limits on current fleet data does not recognize the way in which the changing state of technology affects these relationships as it develops over time. Therefore, the EPA declines to implement the numerical limits from the Novation report.

A.5 Displacement Specific Load and Exemplars

The Alliance also claims in their comment that EPA modeling (specifically the Lumped Parameter Model [LPM]) is "not based on the fundamental factors determining vehicle CO_2 and fuel consumption," quoting text from the vehicle-level Novation report.[26] The "fundamental factors" referred to are the incorporation of "displacement-specific load" (roughly correlated to the inverse of power-to-weight ratio) as a factor in projecting technology effectiveness. The Novation report further explains how changing engine displacement changes powertrain efficiency and technology effectiveness, and specifically how technology benefits change as the engine operational area changes.[27]

The EPA agrees that "displacement-specific load" is an important parameter in determining technology effectiveness. However, both the Alliance and their contractor, Novation, fundamentally misunderstand the purpose and usage of the LPM. In particular, the different vehicle classes used in the LPM have different "exemplar" vehicles, each of which has different engine sizes and road loads, and thus different displacement-specific load. When employing the LPM, individual vehicles in the baseline fleet are mapped to the vehicle class, and the exemplar vehicle, they most resemble. The EPA acknowledges that this modeling process is a simplification, as are all models, and mapping different vehicles in the baseline fleet to the same exemplar will produce both small over-estimates and small under-estimates of technology effectiveness, depending on how close the baseline vehicle is to the exemplar used in the LPM. However, on a fleet-wide average, these small over-and under-estimates of technology effectiveness tend to average out.

The EPA's goal is to estimate technology effectiveness for individual vehicles and across the fleet in the most representative and precise way possible. Therefore, for this Proposed Determination, the EPA has redefined the vehicle effectiveness classes used in the LPM, based in part on vehicle power-to-weight ratio, with the intention of producing effectiveness classes containing vehicles with more similar road loads and engine sizes, as discussed in Section

2.3.3.2. Exemplar characteristics have been defined based on sales-weighted averages of the vehicles in each class. Moreover, the final effectiveness values for each individual vehicle have been adjusted based on that vehicle's power-to-weight ratio. This process ensures the estimates of technology effectiveness are closely representative of the individual vehicles within each effectiveness class, while maintaining fleet-wide average projections of technology effectiveness that are reflective of what would occur in the actual fleet. The methodology used to define the new classes and exemplars is detailed in Section 2.3.1.4 of the TSD.

A.6 Other Studies

Along with the Novation report, the Alliance also cites a 2016 paper written by John Thomas from Oak Ridge National Laboratory[28] as supporting evidence, saying "Novation Analytics and [John Thomas of] Oak Ridge National Laboratory agree that the technology penetrations selected by the OMEGA and Volpe models in the 2012 FRM were insufficient for compliance in MY2022-2025."[29]

However, the Alliance rather overstates the import and conclusions of this paper. In particular, the Alliance neglects to mention the relationship between the Thomas paper and Novation Analytics report, implying through omission that these are separate works. In fact, the methodology in the Thomas paper is essentially identical to that in the Novation reports, and Thomas states in his paper that the work "was inspired and focused by many discussions with Gregg Pannone, Novation Analytics."

Furthermore, the Thomas paper is focused on calculating powertrain efficiency, with no attempt to quantify the fleet mix necessary to meet the 2025 GHG standards, and no reference to the "technology penetrations selected by... OMEGA" as the Alliance claims. The closest reference to technology penetrations in the Thomas paper is the final conclusion, which refers not to OMEGA results, but to the current fleet: "The path to meeting 2025 standards will likely involve significantly larger numbers of hybrid electric powertrain vehicles and/or plug-in vehicles being sold, compared to the current U.S. sales of such vehicles." Although this conclusion is somewhat speculative (i.e., not discussed in the main body of the paper), the EPA notes that the conclusion is not dissimilar to the projections in this Proposed Determination, where the EPA projects MY2025 fleet penetrations of mild HEVs, strong HEVs, and BEVs combined on the order of 25 percent (with more than two thirds of these being mild HEVs), which far exceeds the number in the current fleet (see the Proposed Determination Federal Register notice, Section IV). This does not derogate from the ultimate conclusion in the Proposed Determination that there are compliance pathways to meet the 2025 standards that involve chiefly advanced internal combustion engine technologies rather than strong hybrid or full electrification.

Appendix B Fleet-Wide Analysis of Powertrain Efficiency for Current and Future Technology Packages

B.1 Introduction

In comments received on the Draft TAR, the Alliance of Automobile Manufacturers (AAM) referenced work done by Novation Analytics to recommend that EPA implement "plausibility checks" using a measure of powertrain efficiency and some estimated limitations on this efficiency. As described in Appendix A, EPA believes the numerical limitations on efficiency suggested in the Novation report are not calculated in a robust and scientifically defendable way, and artificially limit potential effectiveness of powertrain components. However, EPA does agree that the calculation of powertrain efficiency does serve as a valuable quality control (QC) tool. For this Proposed Determination, in response to AAM's comments, EPA has incorporated the calculation of powertrain efficiency into its QC process to confirm that the overall effectiveness values applied in this analysis are appropriate.

The approach for this Proposed Determination utilizes data from the individual vehicles in the MY2015 fleet to calculate a measure of powertrain efficiency, defined as the ratio of the energy used to propel the vehicle over the combined test cycle to the fuel energy consumed. Powertrain efficiency values are also calculated for all of the technology packages applied by the OMEGA compliance model. From the distribution of those efficiency values across the fleet, a number of vehicles are investigated closely to confirm that the incremental effectiveness estimates generated by the ALPHA model are closely aligned with those produced by the Lumped Parameter models, not only for the applied technology packages with typical efficiencies, but also for those vehicles and packages with the highest efficiencies. This section describes how powertrain efficiency was calculated, with additional discussion of the results and the QC process provided in TDS Chapter 2.3.3.5.

B.2 Methodology

B.2.1 Definition of Powertrain Efficiency

Powertrain efficiency (η_p), as defined by Thomas,[30] is the ratio of the amount of propulsive energy exerted by a vehicle over a given set of driving conditions to the energy content of the expended fuel. The former term is also denoted as tractive energy ($E_{tractive}$), while the latter is denoted as fuel energy (E_{fuel}). Therefore:

Eq. 1

$$\eta_p = \frac{E_{tractive}}{E_{fuel}}$$

Definition and Calculation of Tractive Energy

Thomas defines tractive energy ($E_{tractive}$, also referred to as powertrain energy) as the energy necessary propel the vehicle at a given rate while also overcoming the cumulative resistive forces acting on it. The difference between these two terms is equal to the total tractive energy that the vehicle exerts. Inertial energy ($E_{inertial}$) is used to calculate the former energy term, and it can be determined using differential analysis of the drive cycle trace to obtain vehicle acceleration (a_{cycle}) which, in combination with the drive cycle's vehicle speed *v(t)* at each point in time, the time increment dt_{cycle}, and the vehicle test mass *m* yields:

Eq. 2

$$E_{inertial} = \sum_{t=0}^{t_{cycle}} dE_{inertial}(t) = \sum_{t=0}^{t_{cycle}} m * a_{cycle}(t) * v(t) * dt_{cycle}$$

The resistive forces due to aerodynamic drag and tire rolling resistance, as well as internal driveline friction are known as road load forces, which are overcome with the expenditure of road load energy (E_{roadload}). The magnitude of the road load force can be represented as a function of the vehicle speed *v(t),* as well as the road load coefficients A, B, and C*,* representing the components to the road load force independent of vehicle speed, proportional to vehicle speed and proportional to the square of the vehicle speed, respectively (Eq. 3). The road load energy can be calculated using Eq. 4. The total resistive energy is negative to represent resisting vehicle motion.

Eq. 3

$$F_{roadload} = A + Bv + Cv^2$$

Eq. 4

$$E_{roadload} = \sum_{t=0}^{t_{cycle}} dE_{roadload}(t) = \sum_{t=0}^{t_{cycle}} -(A + Bv(t) + Cv(t)^2) * v(t) * dt_{cycle}$$

During the drive cycle, braking events must be accounted for, as they represent points where the engine is not directly supplying propulsive energy. Based on Thomas, this analysis assumes that the vehicle is braking when the resistive road load energy alone cannot account for the inertial energy of the vehicle when it is deaccelerating. In other words, for each increment of the drive cycle:

Eq. 5

$$E_{tractive} = \sum_{t=0}^{t_{cycle}} dE_{tractive}(t) = \sum_{t=0}^{t_{cycle}} (dE_{inertial}(t) - dE_{roadload}(t)) \, [dE_{inertial}(t) \geq dE_{roadload}(t)]$$

Similarly, for brake energy (E_{brake}):

Eq. 6

$$E_{brake} = \sum_{t=0}^{t_{cycle}} dE_{brake}(t) = \sum_{t=0}^{t_{cycle}} (dE_{inertial}(t) - dE_{roadload}(t)) \, [dE_{inertial}(t) \leq dE_{roadload}(t)]$$

Definition and Calculation of Fuel Energy

In addition to estimating the tractive energy of the vehicle, the energy theoretically available in the fuel to determine powertrain efficiency must also be calculated. On a per-unit of distance traveled basis (here defined as fuel energy intensity $\dot{E}_{fuel}$), this is:

Eq. 7

$$\dot{E}_{fuel} = \frac{LHV_{fuel}\rho_{fuel}}{MPG}$$

The only quantity related to a particular drive cycle that is necessary in this calculation is the fuel economy (*MPG*) over the given cycle (or harmonically averaged in the case of drive cycle combinations). The relevant fuel properties in this analysis are the lower heating value of the fuel (LHV_{fuel}) and the fuel density (ρ_{fuel}). For this analysis, Tier 2 certification gasoline with a lower heating value of 43.31 MJ/kg, and a density of 0.74 kg/L at 15°C was used to model gasoline-fueled vehicles in the baseline and modeled compliance fleets.

To account for the per-distance aspect of the fuel energy intensity in Eq. 7, when calculating powertrain efficiency, Eq. 1 is modified to utilize the vehicle's tractive energy intensity (energy per unit of distance traveled) instead of the actual tractive energy. By averaging total tractive energy over the entire distance traveled over the drive cycle (d_{cycle}, obtained through integration of the drive cycle trace), we can calculate the average vehicle tractive energy intensity:'

Eq. 8

$$\dot{E}_{tractive,avg} = \frac{E_{tractive}}{d_{cycle}}$$

Eq. 9

$$d_{cycle} = \sum_{t=0}^{t_{cycle}} \mathrm{d}x_{cycle}$$

Combining those equations:

Eq. 10

$$\eta_p = \frac{\dot{E}_{tractive,avg}}{\dot{E}_{fuel}}$$

B.2.2 Considering Tractive Energy Reductions for Future Technology Packages

Powertrain efficiency can be readily calculated for vehicles in the MY2015 fleet using the Equivalent Test Weight and road load coefficient data submitted to EPA by manufacturers for compliance certification. For future technology packages applied to vehicles in the OMEGA compliance model, it is necessary to estimate the test mass and the road load coefficients to account for mass reduction and reductions in tire rolling resistance and aerodynamic drag.

Estimating Vehicle Test Weight and Applying Mass Reduction

Each vehicle has with a curb weight W_{curb}, which is used to denote the unloaded weight of the vehicle. From there, a ballast weight ($W_{ballast,}$ assumed to be 300 lbf.) is added to obtain the vehicle weight for certification testing. The resulting loaded weight W_{load}, listed in Eq. 11, is used to calculate vehicle test mass.

Eq. 11

$$W_{load} = W_{curb} + W_{ballast}$$

For existing vehicles in the baseline fleet, the loaded weight term is assumed to be equal to the vehicle's Equivalent Test Weight (ETW) consistent with EPA's two-cycle certification tests.[31] For future technology packages with mass reduction applied, the loaded weight must be determined differently. Mass reduction is defined as a reduction in curb weight, so the ballast weight must be subtracted from the loaded weight before the mass reduction is applied. For a percent mass reduction *ΔMR (%),* the adjusted loaded weight W'_{load} can be calculated from the original loaded weight W_{load_o} using Eq. 12. Consistent with the approach used in the LPM and OMEGA models for characterizing the effectiveness benefits of mass reduction, the loaded weight values for vehicles with future packages are not rounded into ETW bins.

Eq. 12

$$W'_{load} = \left(\left(W_{load_o} - W_{ballast}\right) * \frac{100 - \Delta\mathrm{MR}\ (\%)}{100}\right) + \mathrm{W_{ballast}}$$

The mass reduction applied to the baseline vehicle to yield the curb weight of the modeled compliance vehicle *ΔMR (%)* is not directly specified by a particular technology package. Instead, both the baseline vehicle technology package and the modeled compliance technology package specify a net mass reduction relative to the curb weight of a null technology package $W_{\mathrm{curb,null}}$, and this quantity is either equal to or greater than the curb weight of the baseline vehicle $W_{\mathrm{curb,base}}$. The baseline curb weight that is reported for the baseline fleet is actually calculated by applying an initial mass reduction to this null curb weight. That net mass reduction between the null curb weight and the baseline curb weight, specified here as *ΔMRnet,o* (%), is more specifically defined as:

Eq. 13

$$\Delta\mathrm{MR_{net,o}}(\%) = 100 * \frac{\mathrm{W_{curb,null}} - \mathrm{W_{curb,base}}}{\mathrm{W_{curb,null}}}$$

The net mass reduction listed for the subsequent model compliance vehicles (i.e. the non-baseline vehicle tech packages) is the net mass reduction applied to those vehicle packages relative to the same null curb weight, resulting in the final vehicle curb weight W_{curb}.

Eq. 14

$$\Delta\mathrm{MR_{net}}(\%) = 100 * \frac{\mathrm{W_{curb,null}} - \mathrm{W_{curb}}}{\mathrm{W_{curb,null}}}$$

The mass reduction ΔMR (%), therefore, is the mass reduction of the model compliance vehicles relative to the curb weight of the baseline vehicle which, unlike the previous mass reduction terms, is not defined relative to $W_{\mathrm{curb,null}}$. Using the above equations, we determine the mass reduction between the baseline and the final tech package to be*:*

Eq. 15

$$\Delta\mathrm{MR}(\%) = \frac{\mathrm{W_{curb,base}} - \mathrm{W_{curb}}}{\mathrm{W_{curb,base}}} = \frac{\Delta\mathrm{MR_{net}}\ (\%) - \Delta\mathrm{MR_{net,o}}\ (\%)}{100 - \Delta\mathrm{MR_{net,o}}(\%)}$$

Road Load Coefficient Estimation and Vehicle Resistive Force Analysis

While estimating vehicle test mass only requires knowing the net mass reduction specified by a given technology package, estimating road load coefficients requires an understanding the forces resisting the motion of the vehicle and the technologies that can affect them. As previously stated, the road load force represents the sum of the forces that the resist the motion of the vehicle. This analysis focuses on five sources of vehicle resistance and the forces associated with them: aerodynamic drag (F_{drag}), tire rolling resistance (F_{tire}), and mechanical drag from brakes (F_{brake}), hubs (F_{hub}), and the neutral drag from the drivetrain ($F_{\text{drivetrain}}$). The sum of all of these resistive forces is denoted as the road load force F_{roadload}:

Eq. 16

$$F_{roadload} = F_{aero} + F_{tire} + F_{brake} + F_{hub} + F_{drivetrain}$$

Aerodynamic drag force is calculated as a function of air density (ρ_a, 2.38e-3 slugs/ft^3, taken to be at STP), aerodynamic drag area ($C_d A_f$) and vehicle velocity (v):

Eq. 17

$$F_{aero} = \frac{1}{2}\rho_a C_d A_f v^2$$

The tire force, which can be estimated using Eq. 18, is dependent on the loaded test weight W_o of the vehicle, the road grade (θ=0°) and on the coefficient of tire rolling resistance C_{TRR}.

Eq. 18

$$F_{tire} = C_{TRR} * W_{load} * \cos(\theta)$$

Of the forces listed above, aerodynamic drag force and tire force are the most important for determining changes in road load coefficient. As such, any attempt to estimate road load coefficients requires having a relation between road load coefficients and these forces. Doing so will allow changes in road load coefficient to be related to changes in drag and tire force or, more specifically the vehicle drag area and tire rolling resistance coefficients.

To obtain an estimate for aerodynamic drag area, Eq. 16-18 are differentiated with respect to velocity, and the differential contributions of resistive forces other than those of aerodynamic drag are negated. This simplification can only be made if the vehicle speed is high enough to allow aerodynamic drag to dominate the total resistive force acting on the vehicle. Hence, by assuming a vehicle operating speed v_a of 110 km/h, aerodynamic drag area can be estimated as:

Eq. 19

$$C_d A_f \approx \frac{B + 2Cv_a}{\rho_a v_a}$$

Using the drag area calculated above, an estimation of the tire rolling resistance coefficient can be obtained by using Eq. 3 and 16-18. An assumed vehicle speed of 50mph was used to obtain values for both road load force and aerodynamic drag. The estimated contributions of brake and hub drag per wheel were obtained from Backstrom[32] and Shevket[33] respectively, assuming a wheel radius of 13in for both sources. Driveline drag forces were assumed to be a constant 20N at an operating speed of 50 mph.

With a way to estimate both drag area and the coefficient of tire rolling resistance, there also needs to be a way to relate those terms to the deductions in aerodynamic drag and tire rolling resistance that are chosen by OMEGA for a particular package. The desired reduction in aerodynamic drag and tire rolling resistance are defined similarly to mass reduction, in that they are both defined relative to a null technology package. Therefore, just like with Eq. 15, the desired aero drag and rolling resistance reductions between the baseline 2015 vehicle and the modeled compliance vehicles are:

Eq. 20

$$\Delta \text{Aero}(\%) = \frac{C_d A_{f_{base}} - C_d A_f}{C_d A_{f_{base}}} = \frac{\Delta \text{Aero}_{net,}(\%) - \Delta \text{Aero}_{net,o}(\%)}{100 - \Delta \text{Aero}_{net,o}(\%)}$$

Eq. 21

$$\Delta \text{TRR}(\%) = \frac{C_{TRR,base} - C_{TRR}}{C_{TRR,base}} = \frac{\Delta \text{TRR}_{net}(\%) - \Delta \text{TRR}_{net,o}(\%)}{100 - \Delta \text{TRR}_{net,o}(\%)}$$

Estimating New Road Load coefficients

With a means by which to relate changes in vehicle parameters to changes in road load coefficients, it is now possible to estimate road load coefficients based on changes to changes in vehicle mass, drag area, and tire rolling resistance. The *B* coefficient is assumed to be constant, while the *C* coefficient changes is proportion to $\Delta AERO\ (\%)$, which is the reduction in aerodynamic drag area ($C_d A_f$), given the relation of both terms to the square of the velocity of the vehicles. The change in the *A* coefficient can be determined by solving Eq. 16-18 for *A* and neglect the aerodynamic drag, brake, hub, and powertrain contributions to the change. The calculations of the adjusted coefficients (A', *B'*, *C'*) from the original baseline coefficients (A_o ,B_o,C_o) are shown in Eq. 23 and 24.

Eq. 22

$$A' = A_o - W_o C_{TRR_o}\left(100 - \left(\frac{100 - \Delta MR(\%)}{100}\right) * \left(\frac{100 - \Delta TRR(\%)}{100}\right)\right) + W_{ballast} C_{TRR_o}\left(\frac{\Delta MR(\%)}{100}\right)(100 - \Delta TRR(\%))/100)$$

Eq. 23

$$B' = B_o$$

Eq. 24

$$C' = C_o * (1 - \frac{\Delta AERO\ (\%)}{100})$$

B.2.3 Displacement Specific Operating Load

After calculating vehicle powertrain efficiency, there needs to be a way to group vehicles based on their power-to-weight ratios. As a rough means of doing so, the “displacement specific operational load” or DSOL was utilized, defined here as the ratio of average cycle tractive road power $P_{tractive}$ to maximum rated engine power P_{rated}:

Eq. 25

$$DSOL = \frac{P_{tractive}}{P_{rated}}$$

While the definition of tractive power is consistent with that of tractive energy, which was calculated to determine powertrain efficiency, Eq. 25 must be modified to utilize the total amount of tractive energy used by the vehicle over the cycle due to the fluctuation in driving conditions and vehicle speed. As such, the maximum rated engine energy E_{rated} can be defined as the total energy exerted by the engine operated at its rated horsepower for the entire drive cycle:

Eq. 26

$$E_{rated} = P_{rated} * \sum_{t=0}^{t_{cycle}} dt = P_{rated} t_{cycle}$$

Therefore:

Eq. 27

$$DSOL = \frac{E_{tractive}}{\mathrm{E}_{\mathrm{rated}}}$$

In this analysis, the modeled compliance vehicle packages are assumed to retain the same DSOL values as their baseline fleet counterparts.

B.2.4 Choice of Drive Cycle

This analysis applies the combined city (FTP) cycle and highway (HWFET) cycle[34] using a 55 percent city/45 percent highway cycle weighting. This yields a combined cycle (comb) fuel economy as a weighted harmonic average of city (C) and highway (H) fuel economy values:

Eq. 28

$$MPG_{comb} = \frac{1}{\frac{0.55}{MPG_C} + \frac{0.45}{MPG_H}}$$

Estimates for combined fuel economy can also be made for gasoline vehicles based on the combined cycle CO_2 emissions for the vehicle. These emission numbers are calculated for all baseline and projected 2025 vehicles through OMEGA. Based on EPA's correlative estimates[35], the combined cycle vehicle unadjusted fuel economy can be approximated as:

Eq. 29

$$MPG_{comb} \approx \frac{8887}{CO_{2,combined}}$$

To account for the combined cycle in our calculations of tractive road energy and DSOL, a weighted average of the corresponding quantities for city and highway drive cycles is used. Thus those quantities for combine cycle analysis are defined as:

Eq. 30

$$\dot{E}_{tractive,avg\,(Comb)} = (0.55 * \dot{E}_{tractive,avg(C)}) + (0.45 * \dot{E}_{tractive,avg\,(H)})$$

Eq. 31

$$DSOL_{Comb} = (0.55 * DSOL_C) + (0.45 * DSOL_H)$$

B.3 Sample Calculation of Powertrain Efficiency

To demonstrate the principles described above in action, a step-by-step calculation of powertrain efficiency and DSOL is shown below. The baseline fleet vehicle chosen was the Toyota Camry (Baseline Entry 2266), given its mid-tier baseline efficiency and the significant vehicle sales in 2015. It also had a sales package in the 2025MY fleet.

Along with the baseline package, this example analysis will also contain a modeled compliance technology package applied to the Camry; specifically, OMEGA package TP07, which was mentioned above. The technologies present in both vehicles is shown in Table 2.1.

Table 2.1 Technical Package Contents of Modeled Baseline and Modeled Compliance Toyota Camry

Tech Pkg.	Tech Package Contents
TP00	|LUB|EFR1|I4|VVT|TRX11|LRRT1|SAX-NA|WRtech- 1.5|WRpen- 0|WRnet- 1.5|
TP07	|EFR2|I4|VVT|Deac-I4|TRX22|IACC2|EPS|Aero2|LRRT2|LDB|SAX-NA|WRtech- 2.5|WRpen- 0|WRnet- 2.5|

Here, we see that the baseline Camry (TP00) has an initial curb weight reduction of 1.5 percent, (WRnet) tire rolling resistance reduction of 10 percent (LRRT1), and no aerodynamic drag reduction relative to the null technology package. The 2025MY GHG standard's compliance analysis technology package (TP07) has reductions to all of these categories relative to the null: 20 percent to aero drag (AERO2), 2.5 percent to curb weight (WRnet- 2.5), and 20 percent to tire rolling resistance (LRRT2). Using these numbers, Eq. 15 and Eqs. 20-21 are used to calculate percent reductions in aero drag, curb weight, and tire rolling resistance between the baseline vehicle and the modeled compliance vehicle. The results are presented in Table 2.2

Table 2.2 Reductions in Aero Drag, Tire Rolling Resistance, and Curb Weight for the Toyota Camry

Tech Package	Curb Weight Reduction from Null (%)	Drag Area Reduction from Null (%)	Tire Rolling Resistance Reduction from Null (%)	Curb Weight Reduction from Base (%)	Drag Area Reduction from Base (%)	Tire Rolling Resistance Reduction from Base (%)
TP00	1.5	0	10	0	0	0
TP07	2.5	20	20	1.02	20	11.1

The original listed parameters necessary for calculating powertrain efficiency and DSOL are shown in Table 2.3

Table 2.3 Powertrain Efficiency and DSOL Calculations Inputs for Baseline Toyota Camry

	A (lbf)	B(lbf/mph)	C(lbf/mph2)	ETW (lbf)	CO2 Emissions (g/mi)	Rated Horsepower (hp)
TP00	27.23	0.04319	0.01937	3500	237.5	178.0

Using Eqs. 16-19, the estimated drag area and tire rolling resistance coefficients can be calculated. The results are shown in Table 2.4

Table 2.4 Calculations of Estimated Aerodynamic Drag Area and Tire Rolling Resistance Coefficient for Baseline Toyota Camry

	Estimated Drag Area (ft2)	Drag Force (lbf)	Total Roadload Force (lbf)	Brake Drag Force (lbf)	Hub Drag Force (lbf)	Neutral Drag Force (lbf)	Tire Resistance Force (lbf)	Estimated Tire Rolling Resistance Coefficient (kg/1000kg)
TP00	7.70	49.22	77.83	1.09	4.90	4.50	18.14	5.18

The values in Table 2.2, Table 2.3, and Table 2.4, along with Eqs. 22-24, we can obtain the necessary input parameters for calculating the powertrain efficiency of the modified compliance package and obtain the corresponding CO2 emission from OMEGA.

Table 2.5 Necessary Input Parameters for Calculation of Powertrain Efficiency and DSOL for Baseline and Modeled Compliance Toyota Camry

	A (lbf)	B(lbf/mph)	C(lbf/mph2)	ETW (lbf)	CO2 Emissions (g/mi)
TP00	27.23	0.04319	0.019374	3500	237.5
TP09	25.07	0.04319	0.015499	3468	176.5

From these parameters, the calculations to determine powertrain efficiency are performed using Eqs. 1-10 and Eqs. 26-31, and the results are listed in Table 2.6.

Table 2.6 Powertrain Efficiency and DSOL Calculations for Baseline and Modeled Compliance Toyota Camry

Tech Pkg	Tractive Energy (kWhr)		Tractive Road Energy Intensity (MJ/km)		TP00 Rated Engine Energy (kWhr)		Combined Cycle			
	Cty	Hwy	Cty	Hwy	Cty	Hwy	TP00 DSOL (*1e-2)	Tractive Road Energy Intensity (MJ/km)	Fuel Energy Intensity (MJ/km)	Powertrain Efficiency (%)
TP00	2.865	1.828	0.4264	0.3981	101.2	28.21	4.46	0.4137	2.015	20.53
TP09	2.702	1.595	0.4020	0.3474	-	-	-	0.3774	1.497	25.21

Appendix C CO_2 Targets with Current Powertrain Designs

How Many of Today's Vehicles Can Meet or Surpass the MY2017-2025 Footprint-based CO2 Targets with Current Powertrain Designs?

As part of this evaluation of the feasibility of the MY2017 to MY2025 standards, EPA updated its analysis of individual vehicles being sold today against the future footprint-based standards. This analysis compares MY2016 and earlier vehicles to the footprint-based standard curves to determine which of these vehicles will meet or be lower than the final MY2017 – MY2025 footprint-based CO_2 targets. The results show that a wide range of current vehicles would already meet or exceed future standards.

Using publicly available data[36], EPA compiled a list of all available vehicles and their 2-cycle CO_2 g/mile performance (that is, the performance over the city and highway compliance tests). No adjustments were made to vehicle CO_2 performance. EPA applied increasing air conditioner credits over time with a phase-in of alternative refrigerant for the generation of HFC leakage reduction credits consistent with the assumed phase-in schedule published in Table C.6 of the Proposed Determination Appendix, Section C. Vehicle footprint data was gathered by EPA from manufacturer submitted CAFE reports[37] and manufacturer websites. The analysis here focuses on MY2016 and prior model years, since MY2016 is the most current complete model year. Production data for MY2016 is based on estimates provided by manufacturers.

As shown in Figure 3.1, approximately 17 percent of MY2016 vehicles already meet or are below the MY2020 standards, given current powertrain performance and air conditioning credits. This represents more than 2.5 million current MY2016 vehicles. It is also important to note that not all vehicles are required to be below their individual targets, and in fact EPA expects that manufacturers will be able to comply with the standards with roughly 50 percent of their production meeting or falling below the footprint based targets.

Manufacturers do have additional opportunities to generate "off-cycle" credits for reduced GHG emissions that are not captured on EPA test cycles. If an additional 5 g/mile credit is applied to all vehicles to account for off-cycle credits, the percentage of MY2016 vehicles that meet or are below the MY2020 targets increases from 17 percent to 21 percent. In MY2015, manufacturers reported an average of 3.0 g/mile[38] with several manufacturers already above 4 g/mile, so an assumption of 5 g/mile of off-cycle credits in MY2020 is likely conservative.

Figure 3.1 also shows that the number of vehicles that meet future standards has been steadily increasing with each passing model year. EPA analysis showed that approximately 5 percent of MY2012 vehicles achieved or were lower than the footprint based MY2020 targets. For MY2016 vehicles, that percentage of vehicles increased to 17 percent (or 21 percent including off-cycle credits). In MY2012 the large majority of vehicles that met or were below the MY2020 targets were hybrid-electric vehicles, but the majority of MY2016 vehicles meeting MY2020 targets are gasoline, non-hybrid vehicles.

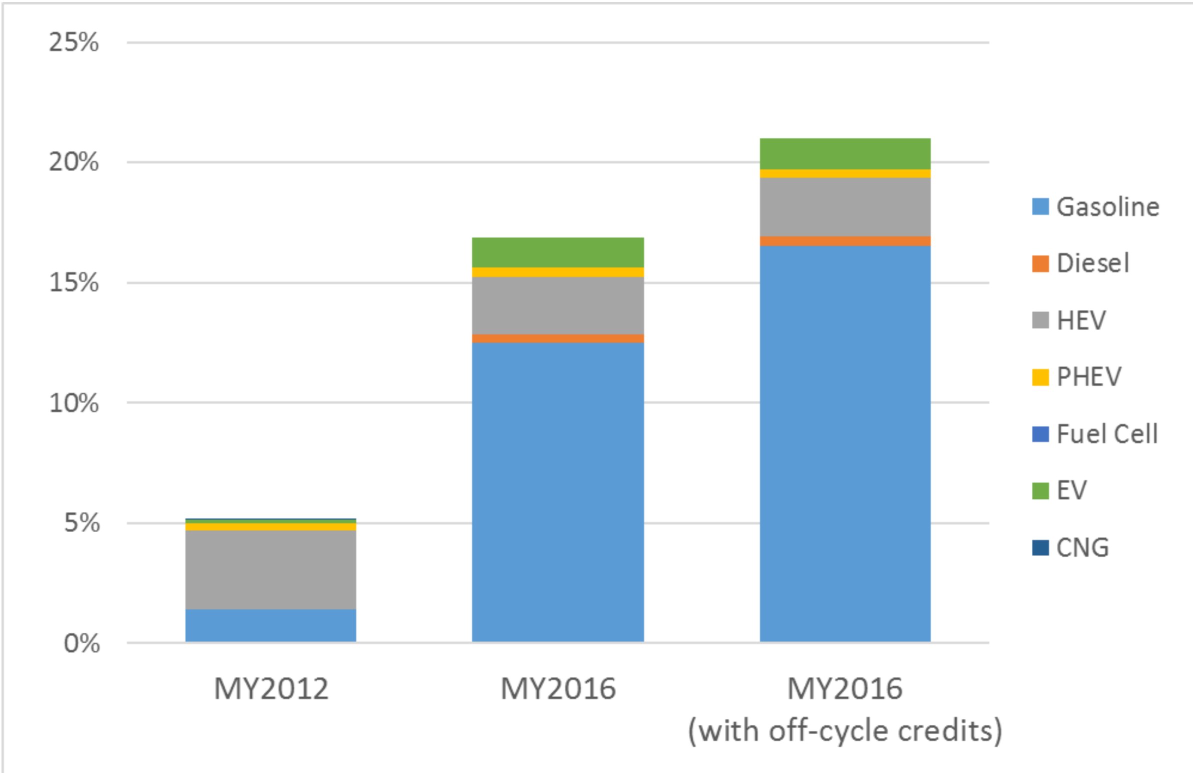


Figure 3.1 Vehicle Production That Meets or Exceeds MY2020 Emission Targets, by Model Year

Table 3.1 shows that more than 100 individual MY2016 vehicle versions already meet or are below the 2020 CO_2 footprint target levels, with current powertrain designs and air conditioning credit generation consistent with the 2012 final rule. The table highlights the vehicles with CO_2 emissions that meet or are lower than the applicable footprint targets from MY2017 to MY2025 in green, and shows the percentage below the target for each model year. Vehicles that are above, but within 5 percent of the targets are highlighted in yellow.

The list of vehicles includes nearly every vehicle type, including midsize cars, sport utility vehicles, and pickup trucks. The vehicles already at or below MY2020 targets also includes vehicles utilizing a variety of powertrain options, including gasoline internal combustion engines, hybrid-electric, plug-in hybrid-electric, and full electric options. Multiple fuel options are also present, including gasoline, diesel, hydrogen, and electricity. Nearly every major manufacturer produces some vehicles that would meet or be lower than the MY2020 footprint CO_2 target with only simple improvements in air conditioning systems.

Table 3.1 Vehicles that Meet or Exceed Future Targets with Current Powertrain Designs

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	BMW	I3 BEV		0	43.5	EV	A1		Subcompact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Chevrolet	Spark EV		0	35.8	EV	A1		Subcompact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	FCA	500e		0	34.7	EV	A1		Minicompact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Ford	Focus Electric FWD		0	43.5	EV	A1		Compact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Kia	Soul Electric		0	43.3	EV	A1		Small Station Wagons	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Mercedes-Benz	B250e		0	49.8	EV	A1		Midsize Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Mercedes-Benz	smart fortwo elec. drive (conv.)		0	26.8	EV	A1		Two Seaters	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Mercedes-Benz	smart fortwo elec. drive (coupe)		0	26.8	EV	A1		Two Seaters	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Mitsubishi	i-MiEV		0	38.4	EV	A1		Subcompact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Nissan	Leaf (24 kW-hr battery pack)		0	44.7	EV	A1		Midsize Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Nissan	Leaf (30 kW-hr battery pack)		0	44.7	EV	A1		Midsize Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Volkswagen	e-Golf		0	42.4	EV	A1		Compact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S (70 kW-hr battery pack)		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S (85 kW-hr battery pack)		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S (90 kW-hr battery pack)		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - 70D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - 75D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - 85D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - 90D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - P85D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model S AWD - P90D		0	53.5	EV	A1		Large Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model X AWD - 75D		0	53.6	EV	A1		Sport Utility Vehicles	T	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model X AWD - 90D		0	53.6	EV	A1		Sport Utility Vehicles	T	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Tesla	Model X AWD - P90D		0	53.6	EV	A1		Sport Utility Vehicles	T	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Toyota	Mirai		0	46.0	Fuel Cell	AV		Subcompact Cars	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	Hyundai	Tuscon		0	45.0	Fuel Cell	A1		Sport Utility Vehicles	C	100%	100%	100%	100%	100%	100%	100%	100%	100%
2016	BMW	I3 REX	132.2	23	43.5	PHEV	A1	0.6	Subcompact Cars	C	95%	96%	96%	97%	97%	97%	97%	97%	97%
2016	Chevrolet	Volt	115.6	30	46.2	PHEV	AV	1.5	Compact Cars	C	92%	92%	93%	93%	94%	93%	93%	93%	92%
2016	Cadillac	ELR	82.8	54	45.9	PHEV	AV	1.4	Subcompact Cars	C	81%	81%	80%	80%	80%	79%	78%	77%	76%
2016	Toyota	Prius Eco	80.8	110	44.6	HEV	AV	1.8	Midsize Cars	C	81%	81%	80%	80%	80%	79%	78%	77%	76%
2016	Cadillac	ELR Sport	82.8	54	45.9	PHEV	AV	1.4	Subcompact Cars	C	81%	81%	80%	80%	80%	79%	78%	77%	76%
2016	Hyundai	Sonata	87.5	64	48.3	PHEV	AM6	2.0	Midsize Cars	C	78%	77%	77%	76%	76%	74%	73%	72%	71%
2016	Ford	Fusion	74.8	86	48.7	PHEV	AV	2.0	Midsize Cars	C	68%	67%	66%	65%	64%	62%	61%	59%	57%
2016	Ford	C-MAX	74.8	86	43.8	PHEV	AV	2.0	Midsize Cars	C	65%	64%	62%	61%	60%	58%	56%	54%	52%
2016	Audi	A3 e-tron ultra	64.3	90	43.7	PHEV	AM-S6	1.4	Compact Cars	C	63%	62%	60%	59%	57%	56%	53%	51%	49%
2016	Audi	A3 e-tron	64.3	105	43.7	PHEV	AM-S6	1.4	Compact Cars	C	55%	54%	52%	51%	49%	46%	44%	41%	38%
2016	BMW	I8	56.6	125	48.5	PHEV	A6	1.5	Subcompact Cars	C	51%	49%	47%	45%	43%	40%	38%	35%	31%
2016	Volvo	XC90 AWD	42.4	166	53.5	PHEV	S8	2.0	Sport Utility Vehicles	T	48%	48%	48%	47%	43%	40%	37%	34%	31%
2016	Toyota	Prius	74.0	120	44.6	HEV	AV	1.8	Midsize Cars	C	49%	47%	45%	43%	41%	38%	35%	32%	29%
2016	BMW	X5 xDrive40e	42.6	169	52.0	PHEV	S8	2.0	Sport Utility Vehicles	T	46%	46%	45%	44%	40%	37%	34%	31%	27%

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	BMW	330e	55.0	128	46.9	PHEV	S8	2.0	Compact Cars	C	48%	46%	44%	42%	39%	37%	34%	30%	27%
2016	Porsche	Cayenne S e-Hybrid	37.5	183	51.8	PHEV	AM8	3.0	Sport Utility Vehicles	T	41%	41%	40%	39%	34%	31%	27%	24%	20%
2016	Chevrolet	Malibu	61.5	145	48.4	HEV	AV	1.8	Midsize Cars	C	42%	40%	37%	35%	32%	29%	26%	22%	19%
2016	Toyota	Prius c	70.8	126	40.6	HEV	AV	1.5	Compact Cars	C	42%	40%	37%	35%	32%	29%	26%	22%	18%
2016	Ford	Fusion Hybrid	59.6	149	48.4	HEV	AV	2.0	Midsize Cars	C	40%	38%	35%	33%	30%	27%	23%	20%	16%
2016	Lincoln	MKZ Hybrid	59.6	149	48.4	HEV	AV	2.0	Midsize Cars	C	40%	38%	35%	33%	30%	27%	23%	20%	16%
2016	Porsche	Panamera S E-Hybrid	43.8	161	52.2	PHEV	AM-S8	3.0	Large Cars	C	40%	37%	35%	32%	29%	26%	22%	19%	15%
2016	Hyundai	Sonata Hybrid SE	58.1	153	48.0	HEV	AM6	2.0	Midsize Cars	C	38%	36%	33%	30%	27%	24%	20%	17%	13%
2016	Toyota	Prius v	58.9	151	46.1	HEV	AV	1.8	Midsize Station Wagons	C	37%	34%	31%	29%	25%	22%	18%	14%	10%
2016	Toyota	Camry Hybrid LE	57.4	155	47.2	HEV	AV	2.5	Midsize Cars	C	36%	34%	31%	28%	25%	21%	18%	14%	10%
2016	Volkswagen	Jetta Hybrid	60.8	146	44.0	HEV	AM-S7	1.4	Compact Cars	C	36%	33%	30%	28%	24%	21%	17%	13%	9%
2016	Hyundai	Sonata Hybrid	56.3	158	47.8	HEV	AM6	2.0	Midsize Cars	C	36%	33%	30%	27%	24%	21%	17%	13%	9%
2016	Lexus	ES 300h	55.2	161	48.0	HEV	AV-S6	2.5	Midsize Cars	C	35%	32%	29%	26%	23%	19%	15%	12%	7%
2016	Mercedes	S 550e		182	54.6	PHEV	A7	3.0	Large Cars	C	34%	31%	28%	26%	22%	19%	15%	11%	7%
2016	Toyota	Avalon Hybrid	55.2	161	47.7	HEV	AV-S6	2.5	Midsize Cars	C	34%	31%	28%	26%	22%	19%	15%	11%	7%
2016	Toyota	Camry Hybrid XLE/SE	54.9	162	47.2	HEV	AV	2.5	Midsize Cars	C	33%	30%	27%	24%	21%	17%	13%	9%	5%
2016	Lexus	CT 200h	57.5	155	42.7	HEV	AV	1.8	Compact Cars	C	30%	27%	24%	21%	17%	13%	9%	5%	0%
2016	Kia	Optima HYBRID EX	51.5	172	48.2	HEV	AM6	2.4	Midsize Cars	C	30%	27%	24%	20%	17%	13%	9%	5%	0%
2016	Toyota	RAV4 Hybrid AWD	44.7	199	44.9	HEV	AV-S6	2.5	Sport Utility Vehicles	T	27%	26%	25%	23%	18%	14%	9%	4%	-1%
2016	Lexus	RX 450h	41.8	213	48.0	HEV	AV-S6	3.5	Sport Utility Vehicles	T	26%	25%	24%	22%	16%	12%	7%	3%	-2%
2016	Ford	C-MAX Hybrid FWD	55.0	162	43.8	HEV	AV	2.0	Large Cars	C	28%	25%	22%	19%	15%	11%	7%	2%	-2%
2016	Kia	Optima Hybrid EX	50.4	176	48.2	HEV	AM6	2.4	Midsize Cars	C	28%	25%	22%	18%	15%	11%	7%	2%	-2%
2016	Lexus	NX 300h AWD	43.5	204	45.1	HEV	AV-S6	2.5	Sport Utility Vehicles	T	25%	24%	23%	21%	15%	11%	6%	2%	-3%
2016	Ford	F150 2WD	28.2	315	76.8	Gasoline	S6	2.7	Standard Pick-up Trucks	T	13%	13%	13%	13%	13%	9%	5%	0%	-5%
2016	Lexus	RX 450h AWD	40.8	218	48.0	HEV	AV-S6	3.5	Sport Utility Vehicles	T	24%	23%	22%	20%	14%	10%	5%	0%	
2016	Ford	F150 2WD	28.2	315	73.6	Gasoline	S6	2.7	Standard Pick-up Trucks	T	13%	13%	13%	13%	13%	9%	4%	0%	
2016	Toyota	Highlander Hybrid AWD LE Plus	38.9	229	48.9	HEV	AV-S6	3.5	Sport Utility Vehicles	T	22%	20%	19%	17%	11%	6%	1%	-4%	
2016	Honda	CR-Z	51.1	174	44.5	HEV	AV-S7	1.5	Two Seaters	C	23%	20%	17%	13%	9%	5%	0%	-4%	
2016	Toyota	Highlander Hybrid AWD	38.7	230	48.9	HEV	AV-S6	3.5	Sport Utility Vehicles	T	21%	20%	18%	16%	10%	6%	1%	-4%	
2016	Subaru	Crosstrek Hybrid	42.5	209	43.2	HEV	AV-S6	2.0	Sport Utility Vehicles	T	21%	19%	18%	16%	10%	5%	0%		
2016	Mercedes-Benz	GLA 250	38.2	233	49.0	Gasoline	AM7	2.0	Midsize Station Wagons	T	20%	19%	17%	15%	9%	5%	0%		
2016	Infiniti	QX60 Hybrid AWD	36.1	246	52.1	HEV	AV-S7	2.5	Sport Utility Vehicles	T	20%	18%	17%	15%	9%	4%	-1%		
2016	Ford	F150 2WD FFV	26.6	335	76.8	Gasoline	A6	3.5	Standard Pick-up Trucks	T	7%	7%	7%	7%	7%	3%	-2%		
2016	Ford	F150 2WD	28.2	315	68.1	Gasoline	S6	2.7	Standard Pick-up Trucks	T	13%	13%	13%	13%	7%	2%	-3%		
2016	Nissan	Murano Hybrid AWD	36.8	242	48.9	HEV	AV-S7	2.5	Midsize Station Wagons	T	17%	15%	14%	12%	5%	0%	-5%		
2016	Honda	Civic 4Dr	48.0	185	45.2	Gasoline	AV	1.5	Midsize Cars	C	19%	16%	12%	8%	4%	0%			
2016	Honda	Civic 2Dr	47.9	186	45.2	Gasoline	AV	1.5	Compact Cars	C	19%	16%	12%	8%	4%	-1%			
2016	Ford	F150 2WD	28.2	315	66.2	Gasoline	S6	2.7	Standard Pick-up Trucks	T	13%	13%	13%	11%	4%	-1%			
2016	Ford	F150 2WD	25.5	349	76.8	Gasoline	S6	3.5	Standard Pick-up Trucks	T	3%	3%	3%	3%	3%	-1%			
2016	Mercedes-Benz	GLA 250 4MATIC	36.0	247	49.0	Gasoline	AM7	2.0	Sport Utility Vehicles	T	15%	13%	12%	10%	3%	-2%			
2016	Mercedes-Benz	GLA 250 4MATIC	36.0	247	49.0	Gasoline	AM7	2.0	Sport Utility Vehicles	T	15%	13%	12%	10%	3%	-2%			
2016	Mazda	Mazda 6	43.1	206	49.4	Gasoline	S6	2.5	Midsize Cars	C	17%	13%	10%	6%	1%	-3%			
2016	Honda	Civic 4Dr	46.8	190	45.2	Gasoline	AV	2.0	Midsize Cars	C	17%	14%	10%	6%	1%	-3%			
2016	Ford	F150 4WD FFV	24.9	357	76.8	Gasoline	A6	3.5	Standard Pick-up Trucks	T	1%	1%	1%	1%	1%	-4%			

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	Volvo	XC90 FWD	32.9	270	53.5	Gasoline	S8	2.0	Sport Utility Vehicles	T	13%	12%	10%	8%	1%	-4%			
2016	Subaru	Outback	37.4	237	45.7	Gasoline	AV-S6	2.5	Sport Utility Vehicles	T	14%	12%	10%	8%	1%	-4%			
2016	Chevrolet	City Express Cargo Van	34.9	254	49.6	Gasoline	AV	2.0	Vans	T	13%	11%	10%	8%	1%	-4%			
2016	Nissan	Rogue AWD	36.8	242	46.4	Gasoline	AV	2.5	Sport Utility Vehicles	T	13%	11%	10%	7%	1%	-5%			
2016	Ford	F150 2WD FFV	26.6	335	68.1	Gasoline	A6	3.5	Standard Pick-up Trucks	T	7%	7%	7%	7%	0%	-5%			
2016	Ford	F150 2WD FFV	26.6	335	68.1	Gasoline	A6	3.5	Standard Pick-up Trucks	T	7%	7%	7%	7%	0%	-5%			
2016	Honda	HR-V 4WD	38.9	229	43.2	Gasoline	AV-S7	1.8	Sport Utility Vehicles	T	13%	11%	10%	7%	0%	-5%			
2016	Honda	HR-V 4WD	38.9	229	43.2	Gasoline	AV	1.8	Sport Utility Vehicles	T	13%	11%	10%	7%	0%	-5%			
2016	BMW	X3 xDrive28d	40.1	254	49.1	Diesel	S8	2.0	Sport Utility Vehicles	T	13%	11%	9%	7%	0%	-5%			
2016	Chevrolet	Cruze	46.6	191	44.8	Gasoline	S6	1.4	Compact Cars	C	16%	12%	8%	5%	0%	-5%			
2016	Chevrolet	Cruze Premier	46.6	191	44.8	Gasoline	S6	1.4	Compact Cars	C	16%	12%	8%	5%	0%	-5%			
2016	Mazda	Mazda 2	50.4	176	39.4	Gasoline	S6	1.5	Compact Cars	C	16%	12%	8%	4%	0%	-5%			
2016	Honda	Civic 2Dr	46.3	192	45.2	Gasoline	AV	2.0	Compact Cars	C	16%	12%	8%	4%	0%	-5%			
2016	Mazda	Mazda 3 4-Door	46.0	193	45.3	Gasoline	S6	2.0	Compact Cars	C	16%	12%	8%	4%	0%				
2016	Subaru	Crosstrek	38.6	230	43.2	Gasoline	AV-S6	2.0	Sport Utility Vehicles	T	12%	10%	9%	6%	-1%				
2016	Mercedes-Benz	Smart fortwo (Coupe)	50.2	177	26.8	Gasoline	AM6	0.9	Two Seaters	C	16%	12%	8%	4%	-1%				
2016	Honda	FIT	50.2	177	40.2	Gasoline	AV	1.5	Small Station Wagons	C	16%	12%	8%	4%	-1%				
2016	Nissan	Altima	44.1	202	47.4	Gasoline	AV	2.5	Midsize Cars	C	16%	12%	8%	4%	-1%				
2016	Toyota	Corolla LE ECO	46.8	190	44.2	Gasoline	AV	1.8	Midsize Cars	C	15%	12%	8%	4%	-1%				
2016	Chevrolet	Colorado 2WD Crew Cab, Long Bed	33.0	308	60.9	Diesel	A6	2.8	Small Pick-up Trucks	T	9%	9%	8%	6%	-1%				
2016	GMC	Canyon 2WD Crew Cab, Long Box	33.0	308	60.9	Diesel	A6	2.8	Sport Utility Vehicles	T	9%	9%	8%	6%	-1%				
2016	Ram	Promaster City	31.5	282	54.9	Gasoline	A9	2.4	Vans	T	11%	10%	8%	6%	-1%				
2016	Scion	iA	49.8	178	40.8	Gasoline	S6	1.5	Subcompact Cars	C	15%	11%	7%	3%	-1%				
2016	Ford	Focus FWD	47.0	189	43.5	Gasoline	M6	1.0	Compact Cars	C	14%	11%	7%	3%	-2%				
2016	Nissan	Sentra FE+	46.1	193	44.4	Gasoline	AV	1.8	Midsize Cars	C	14%	11%	7%	3%	-2%				
2016	Mazda	CX-9 2WD	32.5	273	52.2	Gasoline	S6	2.5	Sport Utility Vehicles	T	10%	9%	7%	5%	-2%				
2016	Ford	F150 2WD FFV	26.6	335	66.2	Gasoline	A6	3.5	Standard Pick-up Trucks	T	7%	7%	7%	5%	-2%				
2016	Nissan	NV200 Cargo Van	34.9	254	47.9	Gasoline	AV	2.0	Vans	T	11%	9%	7%	5%	-2%				
2016	Kia	Optima	42.8	208	48.2	Gasoline	AM7	1.6	Large Cars	C	14%	11%	6%	2%	-2%				
2016	Infiniti	Q70 Hybrid	42.1	211	49.1	HEV	S7	3.5	Midsize Cars	C	14%	10%	6%	2%	-2%				
2016	Mazda	Mazda 3 4-Door	45.1	197	45.3	Gasoline	M6	2.0	Compact Cars	C	14%	10%	6%	2%	-3%				
2016	Mazda	Mazda 3 5-Door	45.1	197	45.3	Gasoline	S6	2.0	Midsize Cars	C	14%	10%	6%	2%	-3%				
2016	Volvo	XC90 AWD	31.7	280	53.5	Gasoline	S8	2.0	Sport Utility Vehicles	T	10%	8%	7%	4%	-3%				
2016	Hyundai	Sonata	42.4	210	48.3	Gasoline	AM7	1.6	Large Cars	C	14%	10%	6%	2%	-3%				
2016	Mercedes-Benz	GLC 300	32.3	275	52.2	Gasoline	A9	2.0	Sport Utility Vehicles	T	10%	8%	6%	4%	-3%				
2016	GMC	C15 Sierra 2WD Crew Cab, Short Box	25.8	345	68.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	4%	4%	4%	4%	-3%				
2016	Chevrolet	C15 Silverado 2WD Crew Cab, Short Box	25.8	345	68.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	4%	4%	4%	4%	-3%				
2016	Toyota	Corolla LE ECO	45.9	194	44.2	Gasoline	AV	1.8	Midsize Cars	C	13%	10%	6%	1%	-3%				
2016	Audi	Q5 Hybrid	34.0	261	48.8	HEV	S8	2.0	Sport Utility Vehicles	T	10%	8%	6%	4%	-3%				
2016	Buick	Encore AWD	38.2	232	42.3	Gasoline	S6	1.4	Sport Utility Vehicles	T	10%	8%	6%	4%	-4%				
2016	BMW	328d	49.6	205	46.9	Diesel	S8	2.0	Compact Cars	C	13%	9%	5%	1%	-4%				
2016	Hyundai	Tucson Eco AWD	36.3	245	45.0	Gasoline	AM7	1.6	Sport Utility Vehicles	T	10%	7%	6%	3%	-4%				
2016	Lexus	NX 300h	44.8	198	45.1	Gasoline	AV-S6	2.5	Sport Utility Vehicles	C	13%	9%	5%	1%	-4%				
2016	Ford	F150 4WD	25.5	348	68.1	Gasoline	S6	2.7	Standard Pick-up Trucks	T	3%	3%	3%	3%	-4%				

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	Ford	Escape AWD	32.9	270	50.5	Gasoline	S6	1.6	Sport Utility Vehicles	T	9%	7%	6%	3%	-4%				
2016	Honda	CR-V 4WD	36.5	243	44.5	Gasoline	AV	2.4	Sport Utility Vehicles	T	9%	7%	6%	3%	-4%				
2016	Ford	F150 2WD	25.5	349	68.1	Gasoline	S6	3.5	Standard Pick-up Trucks	T	3%	3%	3%	3%	-4%				
2016	Lexus	GS 450h	41.6	213	48.5	Gasoline	AV-S8	3.5	Midsize Cars	C	12%	9%	4%	0%	-5%				
2016	Mazda	Mazda 3 5-Door	44.4	200	45.3	Gasoline	M6	2.0	Midsize Cars	C	12%	9%	4%	0%	-5%				
2016	Chevrolet	Cruze Limited ECO	44.8	198	44.8	Gasoline	M6	1.4	Midsize Cars	C	12%	9%	4%	0%	-5%				
2016	Mazda	Mazda 3 4-Door	44.4	200	45.3	Gasoline	S6	2.5	Compact Cars	C	12%	9%	4%	0%	-5%				
2016	Nissan	NV200 NYC Taxi	34.1	261	47.9	Gasoline	AV	2.0	Vans	T	8%	6%	5%	2%					
2016	Ram	1500 4X2 - Regular Cab, 8'0" Box	25.6	347	66.6	Gasoline	A8	3.6	Standard Pick-up Trucks	T	4%	4%	4%	1%					
2016	Mazda	CX-5 4WD	34.9	255	46.1	Gasoline	S6	2.5	Sport Utility Vehicles	T	8%	6%	4%	1%					
2016	Subaru	Forester	36.1	246	44.0	Gasoline	AV	2.5	Sport Utility Vehicles	T	7%	5%	3%	1%					
2016	Ford	F150 4WD	25.5	348	66.2	Gasoline	S6	2.7	Standard Pick-up Trucks	T	3%	3%	3%	1%					
2016	Mercedes-Benz	GLE 300 d 4MATIC	35.9	284	52.2	Diesel	A7	2.1	Sport Utility Vehicles	T	7%	5%	3%	1%					
2016	Mercedes-Benz	GLC 300 4MATIC	31.3	284	52.2	Gasoline	A9	2.0	Sport Utility Vehicles	T	7%	5%	3%	1%					
2016	Nissan	Quest	29.5	301	55.9	Gasoline	AV	3.5	Minivans	T	6%	5%	3%	1%					
2016	Ford	F150 4WD FFV	24.9	357	68.1	Gasoline	A6	3.5	Standard Pick-up Trucks	T	1%	1%	1%	0%					
2016	Ford	F150 4WD FFV	24.9	357	68.1	Gasoline	A6	3.5	Standard Pick-up Trucks	T	1%	1%	1%	0%					
2016	Lincoln	MKT Livery FWD	30.6	290	53.5	Gasoline	S6	2.0	Sport Utility Vehicles	T	6%	5%	3%	0%					
2016	Ford	F150 2WD	25.5	349	66.2	Gasoline	S6	3.5	Standard Pick-up Trucks	T	3%	3%	3%	0%					
2016	Ram	1500 4X4 - Regular Cab, 8'0" Box	29.0	351	66.6	Diesel	A8	3.0	Standard Pick-up Trucks	T	2%	2%	2%	0%					
2016	Jeep	Renegade 4x4	36.7	242	42.7	Gasoline	M6	1.4	Sport Utility Vehicles	T	7%	4%	3%	0%					
2016	Ford	Fiesta SFE FWD	48.4	184	39.0	Gasoline	M5	1.0	Subcompact Cars	C	12%	8%	4%	0%	-5%				
2016	Mazda	Mazda 6	40.8	218	49.4	Gasoline	S6	2.5	Midsize Cars	C	12%	8%	4%	0%					
2016	Acura	RLX	40.3	221	50.1	HEV	AM7	3.5	Midsize Cars	C	12%	8%	4%	0%					
2016	Chevrolet	Cruze	44.4	200	44.8	Gasoline	M6	1.4	Compact Cars	C	11%	8%	3%	-1%					
2016	Mercedes-Benz	Smart fortwo (COUPE)	47.9	185	26.8	Gasoline	M5	0.9	Two Seaters	C	11%	7%	3%	-1%					
2016	Nissan	Versa	47.3	188	41.5	Gasoline	AV	1.6	Compact Cars	C	11%	7%	3%	-1%					
2016	Chevrolet	Malibu	41.1	216	48.4	Gasoline	A6	1.5	Midsize Cars	C	11%	7%	3%	-1%					
2016	Mazda	Mazda 2	47.7	186	39.4	Gasoline	M6	1.5	Compact Cars	C	11%	7%	3%	-2%					
2016	Dodge	Dart Aero	43.4	205	45.6	Gasoline	M6	1.4	Midsize Cars	C	11%	7%	3%	-2%					
2016	Volkswagen	Jetta	44.8	198	44.0	Gasoline	M5	1.4	Compact Cars	C	11%	7%	3%	-2%					
2016	Nissan	Altima SR	41.8	213	47.4	Gasoline	AV-S7	2.5	Midsize Cars	C	11%	7%	2%	-2%					
2016	Mazda	Mazda 3 5-Door	43.5	204	45.3	Gasoline	S6	2.5	Midsize Cars	C	11%	7%	2%	-2%					
2016	Dodge	Dart Aero	43.2	206	45.6	Gasoline	AM6	1.4	Midsize Cars	C	10%	6%	2%	-2%					
2016	Chevrolet	Spark	47.4	188	35.8	Gasoline	AV	1.4	Subcompact Cars	C	10%	6%	2%	-3%					
2016	Honda	Fit	47.3	188	40.2	Gasoline	AV-S7	1.5	Small Station Wagons	C	10%	6%	2%	-3%					
2016	Scion	iA	47.3	188	40.8	Gasoline	M6	1.5	Subcompact Cars	C	10%	6%	2%	-3%					
2016	Toyota	Tacoma 2WD, Double Cab Long bed	27.0	329	61.6	Gasoline	S6	3.5	Small Pick-up Trucks	T	4%	4%	2%	0%					
2016	Volvo	S80 FWD	40.7	219	48.4	Gasoline	S8	2.0	Midsize Cars	C	10%	6%	2%	-3%					
2016	Nissan	Sentra	44.0	202	44.4	Gasoline	AV	1.8	Midsize Cars	C	10%	6%	2%	-3%					
2016	Honda	Accord	41.1	216	47.6	Gasoline	AV	2.4	Midsize Cars	C	10%	6%	1%	-3%					
2016	Chevrolet	Colorado 2WD Crew Cab, Long Bed	27.1	328	60.9	Gasoline	A6	3.6	Small Pick-up Trucks	T	3%	3%	2%	-1%					
2016	GMC	Canyon 2WD Crew Cab, Long Box	27.1	328	60.9	Gasoline	A6	3.6	Small Pick-up Trucks	T	3%	3%	2%	-1%					
2016	Chevrolet	Colorado 2WD	29.3	303	55.6	Gasoline	A6	2.5	Small Pick-up Trucks	T	5%	4%	2%	-1%					

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	GMC	Canyon 2WD	29.3	303	55.6	Gasoline	A6	2.5	Small Pick-up Trucks	T	5%	4%	2%	-1%					
2016	Mazda	Mazda 3 4-Door	42.9	207	45.3	Gasoline	S6	2.5	Compact Cars	C	9%	5%	1%	-3%					
2016	Honda	Odyssey 2WD	29.0	307	55.9	Gasoline	A6	3.5	Minivans	T	4%	3%	1%	-2%					
2016	Ford	F150 2WD	28.2	315	57.5	Gasoline	S6	2.7	Standard Pick-up Trucks	T	3%	2%	1%	-2%					
2016	Mazda	CX-9 4WD	30.6	291	52.2	Gasoline	S6	2.5	Sport Utility Vehicles	T	4%	2%	1%	-2%					
2016	Mercedes-Benz	Metris (Cargo Van)	30.2	294	52.9	Gasoline	A7	2.0	Vans	T	4%	2%	1%	-2%					
2016	Volvo	XC90 AWD	29.9	297	53.5	Gasoline	S8	2.0	Sport Utility Vehicles	T	4%	2%	1%	-2%					
2016	Ford	F150 4WD FFV	24.9	357	66.2	Gasoline	A6	3.5	Standard Pick-up Trucks	T	1%	1%	0%	-2%					
2016	Nissan	Pathfinder 2WD	30.5	292	52.1	Gasoline	AV	3.5	Sport Utility Vehicles	T	4%	2%	0%	-2%					
2016	Volkswagen	Jetta	43.8	203	44.0	Gasoline	S6	1.4	Compact Cars	C	9%	5%	0%	-4%					
2016	Chevrolet	Colorado 2WD	33.0	308	55.6	Diesel	A6	2.8	Small Pick-up Trucks	T	3%	2%	0%	-3%					
2016	GMC	Canyon 2WD	33.0	308	55.6	Diesel	A6	2.8	Sport Utility Vehicles	T	3%	2%	0%	-3%					
2016	Lincoln	MKC AWD	30.9	288	51.2	Gasoline	S6	2.0	Sport Utility Vehicles	T	4%	2%	0%	-3%					
2016	GMC	C15 Sierra 2WD Regular Cab, Long Box	25.8	345	63.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	1%	1%	-1%	-3%					
2016	Chevrolet	C15 Silverado 2WD Regular Cab, Long Box	25.8	345	63.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	1%	1%	-1%	-3%					
2016	Toyota	Tacoma 4WD, Double Cab Long bed	26.1	340	61.6	Gasoline	S6	3.5	Small Pick-up Trucks	T	0%	0%	-1%	-4%					
2016	Buick	Encore AWD	35.7	249	42.3	Gasoline	S6	1.4	Sport Utility Vehicles	T	3%	1%	-1%	-4%					
2016	Chevrolet	Trax AWD	35.7	249	42.3	Gasoline	S6	1.4	Sport Utility Vehicles	T	3%	1%	-1%	-4%					
2016	Ford	Escape AWD	30.9	288	50.5	Gasoline	S6	2.0	Sport Utility Vehicles	T	3%	1%	-1%	-4%					
2016	Chevrolet	Colorado 2WD	28.4	312	55.6	Gasoline	M6	2.5	Small Pick-up Trucks	T	2%	0%	-1%	-4%					
2016	GMC	Canyon 2WD	28.4	312	55.6	Gasoline	M6	2.5	Small Pick-up Trucks	T	2%	0%	-1%	-4%					
2016	Nissan	Murano AWD	31.6	281	48.9	Gasoline	AV-S7	3.5	Midsize Station Wagons	T	3%	0%	-1%	-4%					
2016	Hyundai	Tucson AWD	33.9	263	45.0	Gasoline	AM7	1.6	Sport Utility Vehicles	T	3%	0%	-1%	-4%					
2016	Hyundai	Elantra	42.6	209	45.2	Gasoline	S6	1.8	Midsize Cars	C	8%	4%	0%	-4%					
2016	Toyota	Corolla	43.5	204	44.2	Gasoline	AV	1.8	Midsize Cars	C	8%	4%	0%	-4%					
2016	Dodge	Dart	42.3	210	45.6	Gasoline	M6	1.4	Midsize Cars	C	8%	4%	0%	-5%					
2016	Volvo	V60 FWD	40.7	219	47.4	Gasoline	S8	2.0	Small Station Wagons	C	8%	4%	0%	-5%					
2016	Fiat	500	46.4	192	34.7	Gasoline	M5	1.4	Minicompact Cars	C	8%	4%	0%	-5%					
2016	Mazda	Mazda 6	39.0	228	49.4	Gasoline	M6	2.5	Midsize Cars	C	8%	4%	-1%						
2016	Mercedes-Benz	E 250 BLUETEC	44.3	230	49.8	Diesel	A7	2.1	Midsize Cars	C	8%	4%	-1%						
2016	Volvo	S60 FWD	40.7	219	47.1	Gasoline	S8	2.0	Compact Cars	C	7%	3%	-1%						
2016	Volvo	S60 Inscription FWD	40.7	219	47.1	Gasoline	S8	2.0	Compact Cars	C	7%	3%	-1%						
2016	Honda	CR-Z	46.1	193	36.3	HEV	M6	1.5	Two Seaters	C	8%	3%	-1%						
2016	Infiniti	QX60 Hybrid FWD	37.0	240	52.1	HEV	AV-S7	2.5	Sport Utility Vehicles	C	7%	3%	-1%						
2016	Infiniti	Q50 Hybrid	40.9	217	46.6	HEV	S7	3.5	Compact Cars	C	7%	3%	-1%						
2016	Toyota	Corolla	42.9	207	44.2	Gasoline	AV-S7	1.8	Midsize Cars	C	7%	3%	-1%						
2016	Chevrolet	Spark	46.0	193	35.8	Gasoline	M5	1.4	Subcompact Cars	C	7%	3%	-1%						
2016	Ford	Focus FWD	43.5	204	43.5	Gasoline	S6	1.0	Compact Cars	C	7%	3%	-2%						
2016	Hyundai	Sonata	39.5	225	48.3	Gasoline	S6	2.4	Large Cars	C	7%	3%	-2%						
2016	Honda	Civic4Dr	41.9	212	45.2	Gasoline	M6	2.0	Midsize Cars	C	7%	3%	-2%						
2016	BMW	328d xDrive	46.2	220	46.9	Diesel	S8	2.0	Compact Cars	C	6%	2%	-2%						
2016	BMW	328d xDrive Sports Wagon	46.2	220	46.9	Diesel	S8	2.0	Small Station Wagons	C	6%	2%	-2%						
2016	Nissan	Murano Hybrid FWD	38.8	229	48.9	HEV	AV-S7	2.5	Midsize Station Wagons	C	6%	2%	-2%						
2016	Kia	Optima FE	39.3	226	48.2	Gasoline	S6	2.4	Large Cars	C	6%	2%	-3%						

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	Hyundai	Veloster	42.1	211	44.6	Gasoline	AM6	1.6	Compact Cars	C	6%	2%	-3%						
2016	Audi	A6	37.3	238	50.9	Gasoline	AM-S7	2.0	Midsize Cars	C	6%	2%	-3%						
2016	Toyota	Corolla	42.4	210	44.2	Gasoline	M6	1.8	Midsize Cars	C	6%	2%	-3%						
2016	Ford	Fusion FWD	38.9	228	48.4	Gasoline	S6	1.5	Midsize Cars	C	6%	1%	-3%						
2016	Dodge	Dart	41.1	216	45.6	Gasoline	AM6	1.4	Midsize Cars	C	6%	1%	-3%						
2016	Mazda	Mazda 3 5-Door	41.3	215	45.3	Gasoline	S6	2.5	Midsize Cars	C	5%	1%	-3%						
2016	Honda	Accord	39.4	225	47.6	Gasoline	AV-S7	2.4	Midsize Cars	C	5%	1%	-3%						
2016	Hyundai	Elantra Limited	41.2	216	45.3	Gasoline	S6	1.8	Midsize Cars	C	5%	1%	-4%						
2016	Toyota	Yaris	44.9	198	39.9	Gasoline	M5	1.5	Compact Cars	C	5%	1%	-4%						
2016	Hyundai	Elantra	40.9	217	45.2	Gasoline	M6	1.8	Midsize Cars	C	4%	0%	-4%						
2016	Honda	Civic 2Dr	40.9	217	45.2	Gasoline	M6	2.0	Compact Cars	C	4%	0%	-5%						
2016	Mitsubishi	Outlander Sport 4WD	34.1	260	44.2	Gasoline	AV-S6	2.0	Sport Utility Vehicles	T	2%	0%	-2%	-5%					
2016	BMW	X3 sDrive 28i	31.3	284	49.1	Gasoline	S8	2.0	Sport Utility Vehicles	T	2%	-1%	-2%						
2016	BMW	X3 xDrive28i	31.3	284	49.1	Gasoline	S8	2.0	Sport Utility Vehicles	T	2%	-1%	-2%						
2016	Mercedes-Benz	Metris (Passenger Van)	29.4	303	52.9	Gasoline	A7	2.0	Vans	T	1%	-1%	-2%						
2016	Mercedes-Benz	GLE 350 d 4MATIC	34.0	300	52.2	Diesel	A9	3.0	Sport Utility Vehicles	T	1%	-1%	-3%						
2016	Infiniti	QX60 AWD	29.7	299	52.1	Gasoline	AV-S7	3.5	Sport Utility Vehicles	T	1%	-1%	-3%						
2016	Nissan	Pathfinder 4WD	29.6	300	52.1	Gasoline	AV	3.5	Sport Utility Vehicles	T	1%	-1%	-3%						
2016	BMW	X1 xDrive28i	33.7	264	44.6	Gasoline	S8	2.0	Large Cars	T	1%	-1%	-3%						
2016	Mercedes-Benz	GL 350 BLUETEC 4MATIC	28.3	314	54.8	Gasoline	A7	3.0	Sport Utility Vehicles	T	0%	-1%	-3%						
2016	BMW	X5 xDrive 35d	33.8	301	52.0	Diesel	S8	3.0	Sport Utility Vehicles	T	0%	-2%	-4%						
2016	Jeep	Cherokee FWD	32.7	272	45.7	Gasoline	A9	2.4	Sport Utility Vehicles	T	0%	-2%	-4%						
2016	Jeep	Cherokee FWD	32.7	272	45.7	Gasoline	A9	2.4	Sport Utility Vehicles	T	0%	-2%	-4%						
2016	Subaru	Crosstrek	34.2	260	43.2	Gasoline	M5	2.0	Sport Utility Vehicles	T	0%	-2%	-4%						
2016	Subaru	Legacy	39.7	224	46.5	Gasoline	AV-S6	2.5	Midsize Cars	C	4%	0%	-5%						
2016	Hyundai	Sonata Sport/Limited	38.2	233	48.5	Gasoline	S6	2.4	Large Cars	C	4%	0%							
2016	Volkswagen	Passat	39.1	227	47.2	Gasoline	S6	1.8	Midsize Cars	C	4%	0%							
2016	Ford	Focus FWD	42.1	211	43.5	Gasoline	AM6	2.0	Compact Cars	C	4%	0%							
2016	Ford	Focus FWD FFV	42.1	211	43.5	Gasoline	AM6	2.0	Compact Cars	C	4%	0%							
2016	Chevrolet	Cruze Limited ECO	40.8	218	44.8	Gasoline	A6	1.4	Midsize Cars	C	3%	-1%							
2016	Toyota	Corolla	41.3	215	44.2	Gasoline	A4	1.8	Midsize Cars	C	3%	-1%							
2016	Acura	TLX 2WD	38.3	232	47.8	Gasoline	AM-S8	2.4	Compact Cars	C	3%	-2%							
2016	Kia	Forte	40.8	218	44.5	Gasoline	S6	1.8	Midsize Cars	C	3%	-2%							
2016	Chevrolet	Sonic	44.0	202	41.0	Gasoline	M6	1.4	Compact Cars	C	3%	-2%							
2016	Chevrolet	Sonic 5	44.0	202	41.0	Gasoline	M6	1.4	Small Station Wagons	C	3%	-2%							
2016	Buick	Lacrosse	38.1	233	48.0	HEV	S6	2.4	Midsize Cars	C	3%	-2%							
2016	Mini	Mini Cooper Hardtop 4 Door	43.9	202	38.8	Gasoline	M6	1.5	Subcompact Cars	C	3%	-2%							
2016	Mercedes-Benz	CLA 250	40.4	220	45.0	Gasoline	AM7	2.0	Compact Cars	C	3%	-2%							
2016	Scion	iM	42.7	208	42.3	Gasoline	AV-S7	1.8	Midsize Cars	C	3%	-2%							
2016	Subaru	Impreza	41.9	212	43.0	Gasoline	AV-S6	2.0	Compact Cars	C	2%	-2%							
2016	Subaru	Impreza Wagon	41.9	212	43.0	Gasoline	AV-S6	2.0	Small Station Wagons	C	2%	-2%							
2016	Toyota	Yaris	43.8	203	39.9	Gasoline	A4	1.5	Compact Cars	C	2%	-2%							
2016	Chevrolet	Cruze Limited	40.4	220	44.8	Gasoline	M6	1.4	Midsize Cars	C	2%	-2%							
2016	Honda	HR-V 2WD	41.7	213	43.2	Gasoline	AV	1.8	Sport Utility Vehicles	C	2%	-2%							

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	Honda	HR-V 2WD	41.7	213	43.2	Gasoline	AV-S7	1.8	Sport Utility Vehicles	C	2%	-2%							
2016	Mercedes-Benz	E 250 BLUETEC 4MATIC	41.9	243	49.8	Diesel	A7	2.1	Midsize Cars	C	2%	-2%							
2016	BMW	535d	40.5	251	51.5	Diesel	S8	3.0	Midsize Cars	C	2%	-3%							
2016	Mazda	CX-5 2WD	39.2	227	46.1	Gasoline	M6	2.0	Sport Utility Vehicles	C	2%	-3%							
2016	BMW	528i	35.4	251	51.5	Gasoline	S8	2.0	Midsize Cars	C	2%	-3%							
2016	Nissan	Sentra	40.5	219	44.4	Gasoline	M6	1.8	Midsize Cars	C	2%	-3%							
2016	Chevrolet	Cruze Limited	40.1	222	44.8	Gasoline	S6	1.4	Midsize Cars	C	1%	-3%							
2016	Toyota	Camry	38.2	233	47.2	Gasoline	S6	2.5	Midsize Cars	C	1%	-3%							
2016	Ford	Fusion FWD	37.3	238	48.4	Gasoline	S6	1.5	Midsize Cars	C	1%	-3%							
2016	Kia	Optima	37.5	237	48.2	Gasoline	S6	2.4	Large Cars	C	1%	-3%							
2016	Mazda	CX-5 2WD	38.9	228	46.1	Gasoline	S6	2.5	Sport Utility Vehicles	C	1%	-3%							
2016	Hyundai	Veloster	40.1	222	44.6	Gasoline	M6	1.6	Compact Cars	C	1%	-3%							
2016	Honda	FIT	43.1	206	40.2	Gasoline	M6	1.5	Small Station Wagons	C	1%	-4%							
2016	Mini	Mini Cooper Hardtop 2 Door	43.0	206	38.8	Gasoline	M6	1.5	Subcompact Cars	C	1%	-4%							
2016	Infiniti	Q50 Hybrid AWD	38.2	232	46.6	HEV	S7	3.5	Compact Cars	C	0%	-4%							
2016	Buick	Regal	38.1	233	46.8	HEV	S6	2.4	Midsize Cars	C	0%	-4%							
2016	GMC	C15 Sierra 2WD Crew Cab, Standard Box	24.0	370	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-3%	-5%				
2016	Ford	F150 4WD	23.7	375	76.8	Gasoline	S6	3.5	Standard Pick-up Trucks	T	-5%	-5%	-5%	-5%	-5%				
2016	Chevrolet	C15 SilveradoO 2WD Crew Cab, Standard Box	24.0	370	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-3%	-5%				
2016	GMC	C15 Sierra 2WD FFV Crew Cab, Standard Box	24.0	371	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-3%	-5%				
2016	Chevrolet	C15 Silverado 2WD FFV Crew Cab, Standard Box	24.0	371	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-3%					
2016	Chevrolet	C15 Silverado 2WD Cab Chassis	23.9	372	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-4%	-4%	-4%	-4%					
2016	GMC	C15 Sierra 2WD Cab Chassis	23.9	372	72.5	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-4%	-4%	-4%	-4%					
2016	Chevrolet	K15 Silverado 4WD Crew Cab, Short Box	24.3	366	68.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	-2%	-2%	-2%	-3%					
2016	GMC	K15 Sierra 4WD Crew Cab, Short Box	24.3	366	68.0	Gasoline	A6	4.3	Standard Pick-up Trucks	T	-2%	-2%	-2%	-3%					
2016	GMC	C15 Sierra 2WD Crew Cab, Short Box	24.0	370	68.0	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-4%					
2016	Chevrolet	C15 Silverado 2WD Crew Cab, Short Box	24.0	370	68.0	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-4%					
2016	GMC	C15 Sierra 2WD FFV Crew Cab, Short Box	24.0	371	68.0	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-4%					
2016	Chevrolet	C15 Silverado 2WD FFV Crew Cab, Short Box	24.0	371	68.0	Gasoline	A6	5.3	Standard Pick-up Trucks	T	-3%	-3%	-3%	-4%					
2016	Chevrolet	Colorado 4WD Crew Cab, Long Bed	29.9	340	60.9	Diesel	A6	2.8	Small Pick-up Trucks	T	-1%	-1%	-2%	-5%					
2016	GMC	Canyon 4WD Crew Cab, Long Box	29.9	340	60.9	Diesel	A6	2.8	Sport Utility Vehicles	T	-1%	-1%	-2%	-5%					
2016	Ford	F150 4WD	23.7	375	68.1	Gasoline	S6	3.5	Standard Pick-up Trucks	T	-5%	-5%	-5%						
2016	Ram	1500 HFE 4X2	31.4	324	56.8	Diesel	A8	3.0	Standard Pick-up Trucks	T	-1%	-1%	-3%						
2016	Chevrolet	Colorado 4WD Crew Cab, Long Bed	25.7	346	60.9	Gasoline	A6	3.6	Small Pick-up Trucks	T	-2%	-2%	-4%						
2016	GMC	Canyon 4WD Crew Cab, Long Box	25.7	346	60.9	Gasoline	A6	3.6	Small Pick-up Trucks	T	-2%	-2%	-4%						
2016	Ram	1500 HFE 4X2	27.2	327	56.8	Gasoline	A8	3.6	Standard Pick-up Trucks	T	-2%	-2%	-4%						
2016	Ford	Edge AWD	30.0	297	50.5	Gasoline	S6	2.0	Sport Utility Vehicles	T	0%	-3%	-5%						
2016	Chevrolet	Equinox AWD	30.8	289	48.8	Gasoline	A6	2.4	Sport Utility Vehicles	T	0%	-3%	-5%						
2016	Chevrolet	Equinox AWD	30.8	289	48.8	Gasoline	A6	2.4	Sport Utility Vehicles	T	0%	-3%	-5%						
2016	GMC	Terrain AWD	30.8	289	48.8	Gasoline	A6	2.4	Sport Utility Vehicles	T	0%	-3%	-5%						
2016	Toyota	Tacoma 2WD	27.5	323	55.8	Gasoline	S6	2.7	Small Pick-up Trucks	T	-2%	-3%	-5%						
2016	Ford	F150 4WD	23.7	375	66.2	Gasoline	S6	3.5	Standard Pick-up Trucks	T	-5%	-5%	-5%						
2016	Toyota	RAV4 AWD	32.9	270	44.9	Gasoline	S6	2.5	Sport Utility Vehicles	T	-1%	-3%							
2016	Land Rover	Range Rover Evoque	31.7	280	46.6	Gasoline	S9	2.0	Sport Utility Vehicles	T	-1%	-4%							

Model Year	Manufacturer	Vehicle	Fuel Economy (mpg)	Tailpipe CO_2 (g/mile)	Footprint (ft^2)	Powertrain Type	Trans-mission	Engine Disp. (L)	Vehicle Class	Car/ Truck	Compliance								
											2017	2018	2019	2020	2021	2022	2023	2024	2025
2016	Nissan	Pathfinder 4WD Platinum	28.8	309	52.1	Gasoline	AV	3.5	Sport Utility Vehicles	T	-2%	-4%							
2016	Honda	Pilot 4WD	29.2	305	51.3	Gasoline	S9	3.5	Sport Utility Vehicles	T	-2%	-4%							
2016	Chevrolet	Colorado 4WD	27.2	326	55.6	Gasoline	A6	2.5	Small Pick-up Trucks	T	-3%	-4%							
2016	GMC	Canyon 4WD	27.2	326	55.6	Gasoline	A6	2.5	Small Pick-up Trucks	T	-3%	-4%							
2016	Ford	Transit Connect Van 2WD	32.6	273	44.8	Gasoline	S6	1.6	Vans	T	-2%	-4%							
2016	Land Rover	Range Rover Sport TDV6	32.4	314	53.1	Diesel	S8	3.0	Sport Utility Vehicles	T	-3%	-4%							
2016	Land Rover	Range Rover TDV6	32.4	314	53.1	Diesel	S8	3.0	Sport Utility Vehicles	T	-3%	-4%							
2016	Subaru	Forester	33.0	269	44.0	Gasoline	AV-S8	2.0	Sport Utility Vehicles	T	-2%	-4%							
2016	Lexus	NX 200t AWD	32.3	275	45.1	Gasoline	S6	2.0	Sport Utility Vehicles	T	-2%	-5%							
2016	Dodge	Durango RWD	28.1	316	53.2	Gasoline	A8	3.6	Sport Utility Vehicles	T	-3%	-5%							
2016	Chevrolet	Colorado 2WD	27.1	328	55.6	Gasoline	A6	3.6	Small Pick-up Trucks	T	-3%	-5%							
2016	GMC	Canyon 2WD	27.1	328	55.6	Gasoline	A6	3.6	Small Pick-up Trucks	T	-3%	-5%							
2016	Toyota	Tacoma 2WD, Access Cab or Double/short	27.0	329	55.8	Gasoline	S6	3.5	Small Pick-up Trucks	T	-4%	-5%							
2016	Toyota	RAV4 Limited AWD/SE AWD	32.3	275	44.9	Gasoline	S6	2.5	Sport Utility Vehicles	T	-2%	-5%							
2016	BMW	528i xDrive	34.8	255	51.5	Gasoline	S8	2.0	Midsize Cars	C	0%	-5%							
2016	Subaru	Impreza Sport	41.0	217	43.0	Gasoline	AV-S6	2.0	Small Station Wagons	C	0%	-5%							
2016	Kia	Rio ECO	41.7	213	42.1	Gasoline	S6	1.6	Compact Cars	C	0%	-5%							
2016	Mazda	Mazda 3 4-Door	39.1	227	45.3	Gasoline	M6	2.5	Compact Cars	C	0%	-5%							
2016	Ford	Focus FWD FFV	40.5	220	43.5	Gasoline	AM-S6	2.0	Compact Cars	C	0%	-5%							
2016	Nissan	Rogue FWD	38.1	233	46.4	Gasoline	AV	2.5	Sport Utility Vehicles	C	0%	-5%							
2016	Ford	Focus FWD	40.4	220	43.5	Gasoline	AM-S6	2.0	Compact Cars	C	0%	-5%							
2016	Toyota	Sienna	26.8	331	56.1	Gasoline	S6	3.5	Minivans	T	-4%								
2016	Ford	Transit Connect Wagon FWD	32.3	275	44.8	Gasoline	S6	1.6	Vans	T	-3%								
2016	Audi	Q5	34.4	296	48.8	Diesel	S8	3.0	Sport Utility Vehicles	T	-3%								
2016	BMW	X4 xDrive28i	29.8	298	49.1	Gasoline	S8	2.0	Sport Utility Vehicles	T	-3%								
2016	Toyota	Tacoma 4WD	26.8	332	55.8	Gasoline	M5	2.7	Small Pick-up Trucks	T	-5%								
2016	Subaru	Forester	32.6	273	44.0	Gasoline	M6	2.5	Sport Utility Vehicles	T	-3%								
2016	Acura	MDX 4WD	28.9	307	50.8	Gasoline	S9	3.5	Sport Utility Vehicles	T	-3%								
2016	Nissan	Frontier 2WD	27.4	324	54.0	Gasoline	M5	2.5	Small Pick-up Trucks	T	-4%								
2016	Mitsubishi	Outlander Sport 4WD	32.2	276	44.2	Gasoline	AV-S6	2.4	Sport Utility Vehicles	T	-4%								
2016	Audi	Q5	29.6	301	48.8	Gasoline	S8	2.0	Sport Utility Vehicles	T	-5%								
2016	Jeep	Cherokee FWD	31.1	285	45.7	Gasoline	A9	3.2	Sport Utility Vehicles	T	-5%								
2016	Ford	Taurus FWD	34.7	256	51.3	Gasoline	S6	2.0	Large Cars	C	-1%								
2016	Kia	Rio	41.6	214	42.1	Gasoline	M6	1.6	Compact Cars	C	-1%								
2016	Lincoln	MKC FWD	34.7	256	51.2	Gasoline	S6	2.0	Sport Utility Vehicles	C	-1%								
2016	Dodge	Dart	38.7	230	45.6	Gasoline	M6	2.0	Midsize Cars	C	-1%								
2016	Mazda	Mazda 3 5-Door	38.9	228	45.3	Gasoline	M6	2.5	Midsize Cars	C	-1%								
2016	Hyundai	Accent	41.8	212	41.7	Gasoline	M6	1.6	Compact Cars	C	-1%								
2016	Ford	Escape FWD	35.2	253	50.5	Gasoline	S6	1.6	Sport Utility Vehicles	C	-1%								
2016	Nissan	Versa	42.0	212	41.5	Gasoline	M5	1.6	Compact Cars	C	-1%								
2016	Kia	Forte	39.4	225	44.5	Gasoline	M6	1.8	Midsize Cars	C	-1%								
2016	Cadillac	CT6	32.9	270	54.1	Gasoline	S8	2.0	Large Cars	C	-1%								
2016	Mazda	CX-3 2WD	42.5	209	40.7	Gasoline	S6	2.0	Compact Cars	C	-1%								
2016	Kia	Rio	41.3	215	42.1	Gasoline	S6	1.6	Compact Cars	C	-1%								

Appendix D EPA Comparison Testing performed on a MY2014 Mazda SKYACTIV-G Engine using Different Fuels

As part of the agency's ongoing engine technology benchmarking activities, EPA has independently generated a set of fuel difference maps using its data previously generated with fuels having different properties, including differences in RON. The engine benchmarked was a MY2014 Mazda SKYACTIV-G 2.0L 4-cylinder engine with a 13:1 geometric CR.

The data for this analysis came from engine dynamometer tests previously conducted by EPA using a Tier 2 certification gasoline and a LEV III gasoline (see Table 4.1, fuels A and B, respectively).[B] EPA also conducted chassis dynamometer tests using a Tier 2 certification gasoline and a Tier 3 certification gasoline (see Table 4.1, fuels C and D, respectively). Two of the tested fuels, Fuel B and Fuel D, had RON levels comparable to the RON reported by AAM/USCAR (92 RON and 91 RON respectively) and AKI levels and ethanol content very close to those of regular-grade "pump gasoline".

Fuels A and C both represent Tier 2 certification gasoline, which (as noted above) is the gasoline used for Federal GHG compliance testing. Both are E0 fuels (0 percent ethanol) with similar distillation properties. Net energy content is slightly higher for Fuel C. Fuels B and D represent LEV III and Tier 3 certification fuels, respectively, that will be used for compliance with California LEV III and Federal Tier 3 emissions standards for criteria pollutants. Both are E10 fuels (approximately 10 percent by volume ethanol) as per California LEV III and U.S. Federal Tier 3 fuel specifications and have properties that are close to the average properties of "regular grade" gasoline in California and the U.S., respectively. Fuel B has approximately 1-point higher RON and AKI and lower DVPE than Fuel D, but net energy contents were nearly identical for both fuels.

[B] LEV III and Tier 3 certification gasoline are remarkably similar. The chief differences are an approximately 2 psi lower Dry Vapor Pressure Equivalent and associated distillation properties.

Table 4.1 Measured Fuel Properties for Four Gasolines Used for Engine and Vehicle Benchmarking

		Test Fuels			
Property	Unit	Fuel A (Tier 2 Gasoline, FTAG 23945)	Fuel B (LEV III Gasoline, FTAG 24350)	Fuel C (Tier 2 Gasoline, FTAG 25278)	Fuel D (Tier 3 Gasoline, FTAG 25206)
Research Octane Number (RON), ASTM D2699	-	97.1	92.4	96.5	91.0
Motor Octane Number (MON), ASTM D2700	-	88.2	83.8	88.6	83.5
Antiknock Index (AKI), (RON+MON)/2	-	92.6	88.1	92.6	87.2
Net Heat of Combustion, ASTM D4809	MJ/kg	NA	NA	43.18	41.71
Net Heat of Combustion, ASTM D240	MJ/kg	42.89	41.76	NA	NA
Dry Vapor Pressure Equivalent (DVPE), ASTM D5191	psi	9.17	7.01	8.95	8.75
Distillation, ASTM D86 Initial boiling point	°F	88.3	109.9	89.4	100.0
10% evaporated	°F	123.4	138.1	125.6	129.0
50% evaporated	°F	223.0	213.2	222.6	209.9
90% evaporated	°F	322.8	317.6	317.3	321.7
Evaporated final boiling point	°F	389.4	352.4	405.9	387.1
Aromatics, ASTM D5769 Total Aromatic HC	volume %	33.51	23.03	32.3	23.8
C6 Aromatics (benzene)	volume %	0.33	0.67	0.05	0.56
C7 Aromatics (toluene)	volume %	18.56	5.79	20.0	6.2
Olefins, ASTM D6550	mass %	2.0	4.7	NA	6.4
Olefins, ASTM D6729	volume %	NA	NA	0.10	6.4
Ethanol, ASTM D5599	volume %	0.0	9.64	0.0	9.86
Oxygen, ASTM D5599	mass %	0.0	3.54	0.0	3.64
Sulfur, ASTM D2622	mg/kg	38.5	NA	39.6	8.3
Sulfur, ASTM D5453	mg/kg	NA	9.55	NA	NA

Because units for the AAM/USCAR "difference map" comparison were not provided by AAM, EPA engineering staff prepared difference map comparisons on both a percentage and an absolute basis and for both fuel volumetric- and mass-flows (see Figure 4.1 through Figure 4.4) and without correction for differences in the net energy content (also known as "lower heating value" or LHV) for Fuel A and Fuel B in order to provide points of comparison to the AAM data. The same comparisons are also shown with a correction applied for net energy content

(Figure 4.5 through Figure 4.8), as well as on a brake thermal energy basis in Figure 4.9 and on a CO_2 emissions basis in Figure 4.10.

We believe the most appropriate way to compare fuels is either on a CO_2 basis (i.e., the primary tailpipe GHG for compliance with EPA standards), a brake thermal energy basis (i.e., independent of LHV) or on a fuel consumption basis that corrects the fuels that are compared to results achievable assuming a common net energy content. Note that each of EPA's comparison maps are comprised of a numerical fit of more than one-hundred engine speed-load operating points. Fits using fewer points may reduce the fidelity of the resulting map or "difference map" and can introduce interpolation errors.

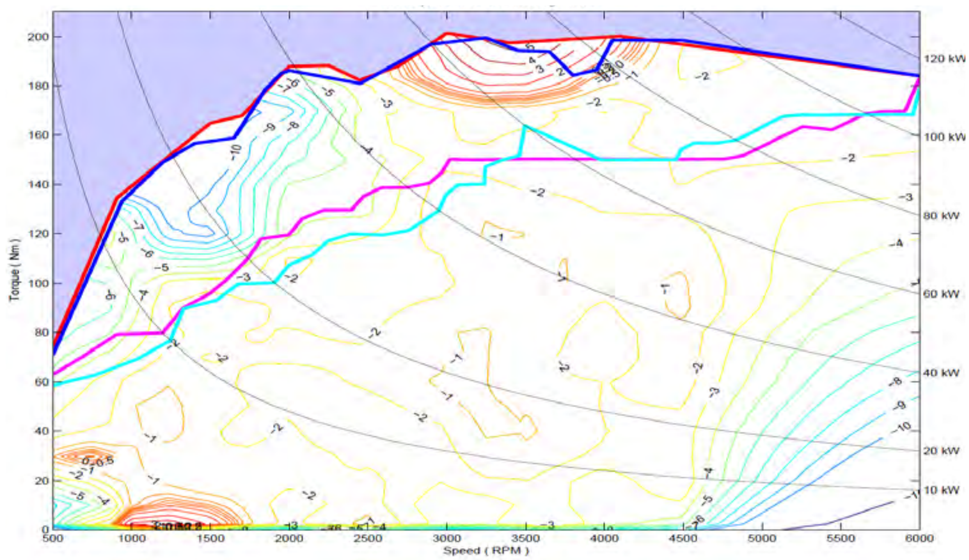


Figure 4.1 Map of the Percentage Difference in Volumetric Fuel Flow for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are not corrected for differences in the net energy content between the two fuels.

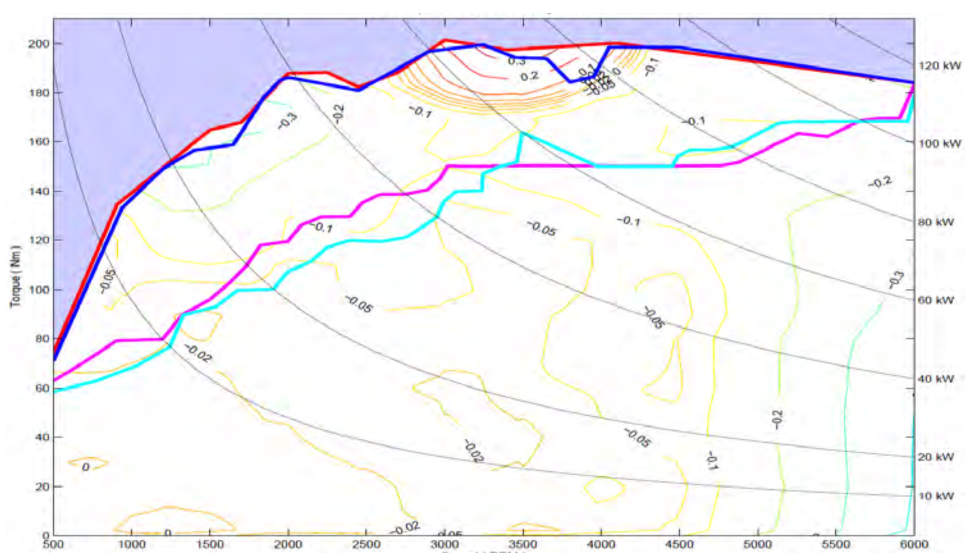


Figure 4.2 Map of the Absolute Difference in Volumetric Fuel Flow (In Units of Ml/S) For A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine With A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are not corrected for differences in the net energy content between the two fuels.

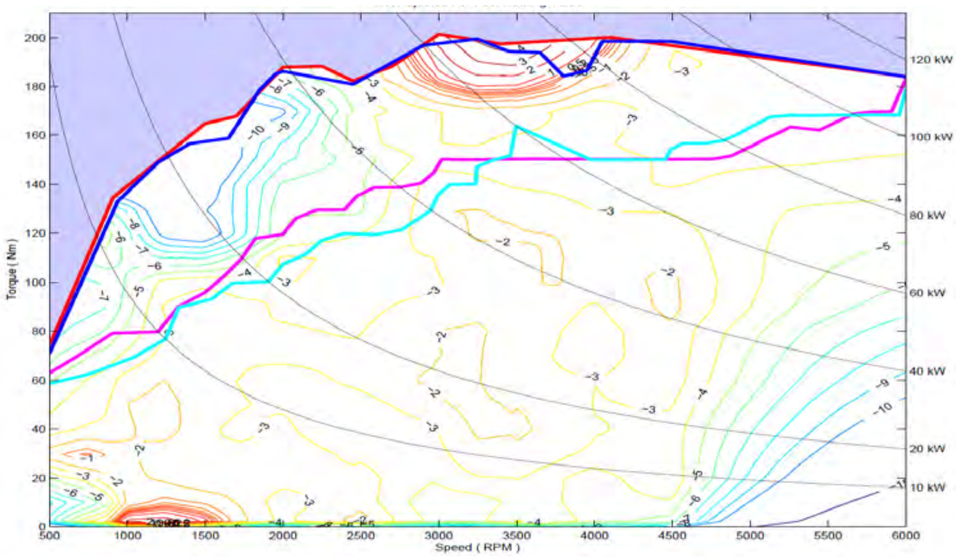


Figure 4.3 Map of the Percentage Difference in Fuel Mass Flow for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine With A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are not corrected for differences in the net energy content between the two fuels.

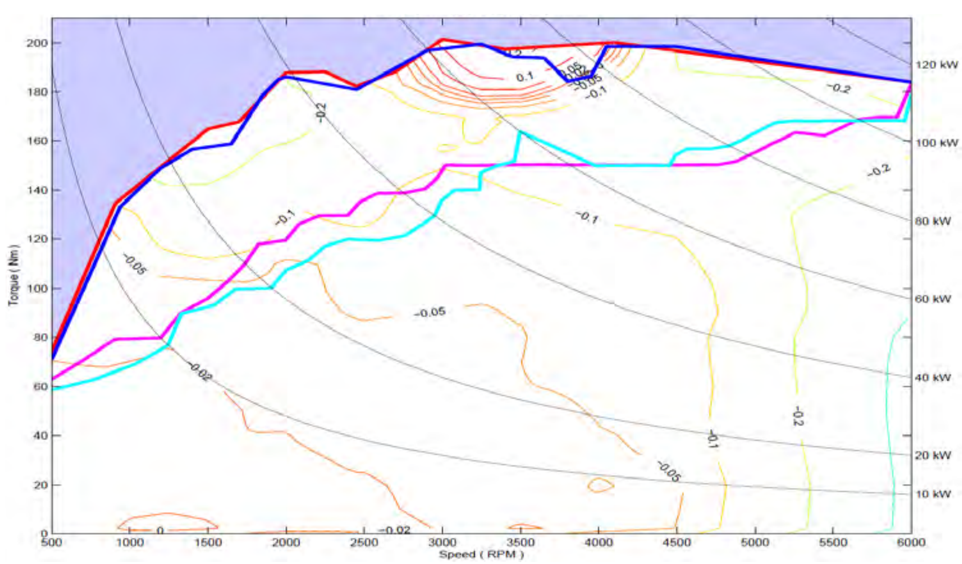


Figure 4.4 Map of the Absolute Difference in Fuel Mass Flow (In Units of G/S) For A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are not corrected for differences in the net energy content between the two fuels.

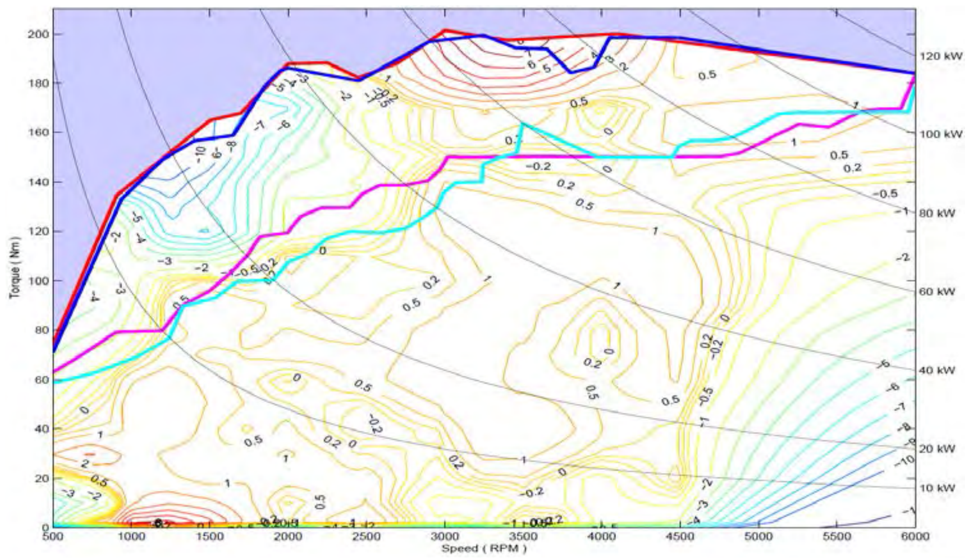


Figure 4.5 Map of the Percentage Difference in Volumetric Fuel Flow for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are corrected for differences in the net energy content between the two fuels to allow a direct comparison of the impacts of other fuel property differences.

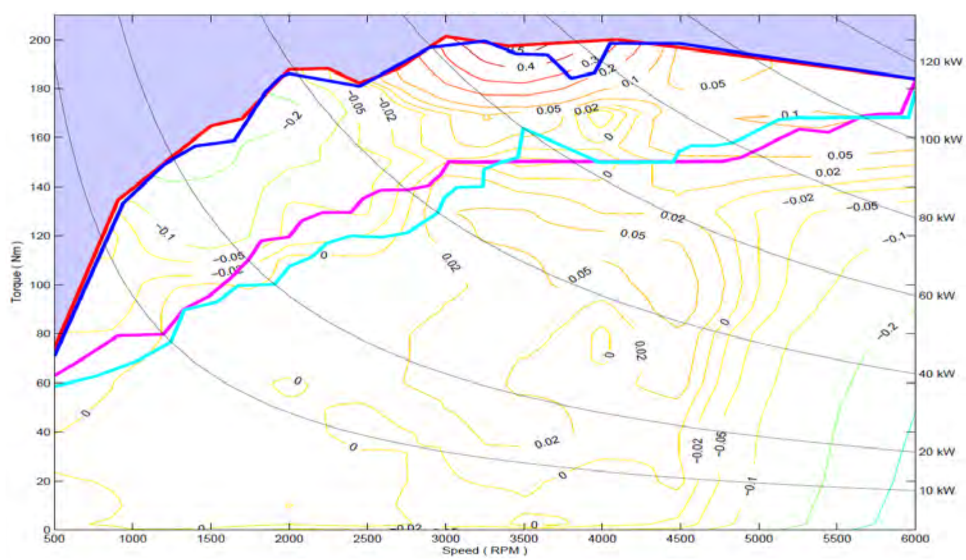


Figure 4.6 Map of the Absolute Difference in Volumetric Fuel Flow (In Units of Ml/S) for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are corrected for differences in the net energy content between the two fuels to allow a direct comparison of the impacts of other fuel property differences.

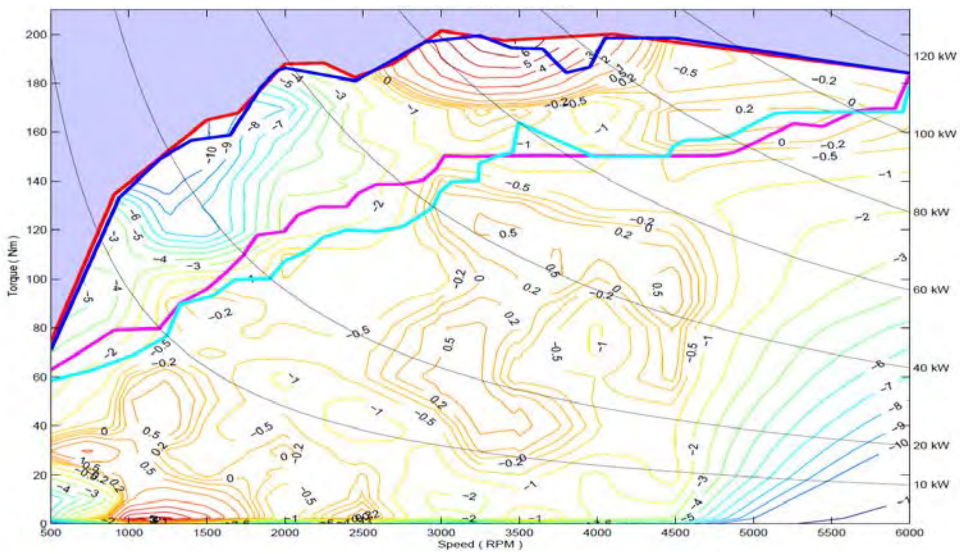


Figure 4.7 Map of the Percentage Difference in Fuel Mass Flow for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are corrected for differences in the net energy content between the two fuels to allow a direct comparison of the impacts of other fuel property differences.

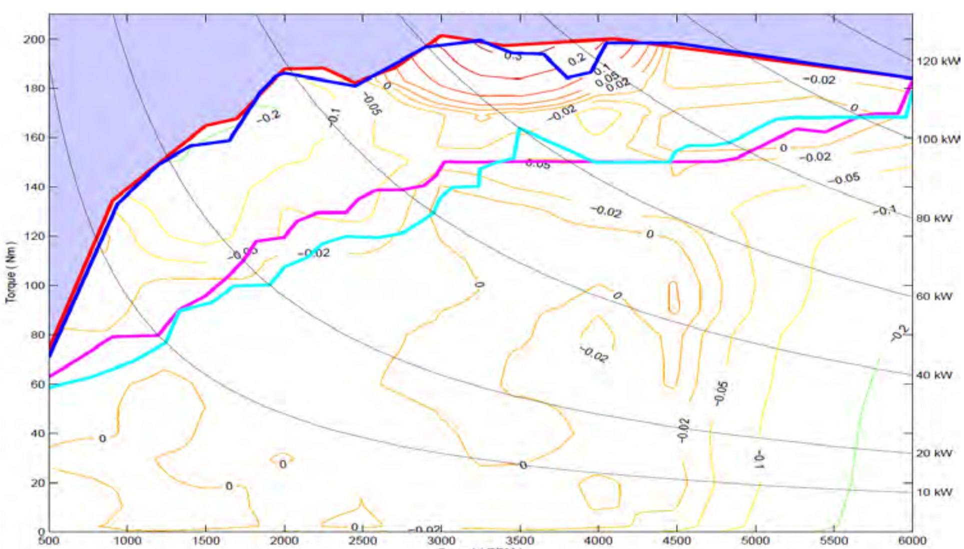


Figure 4.8 Map of the Absolute Difference in Fuel Mass Flow (In Units of G/S) For A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are corrected for differences in the net energy content between the two fuels to allow a direct comparison of the impacts of other fuel property differences.

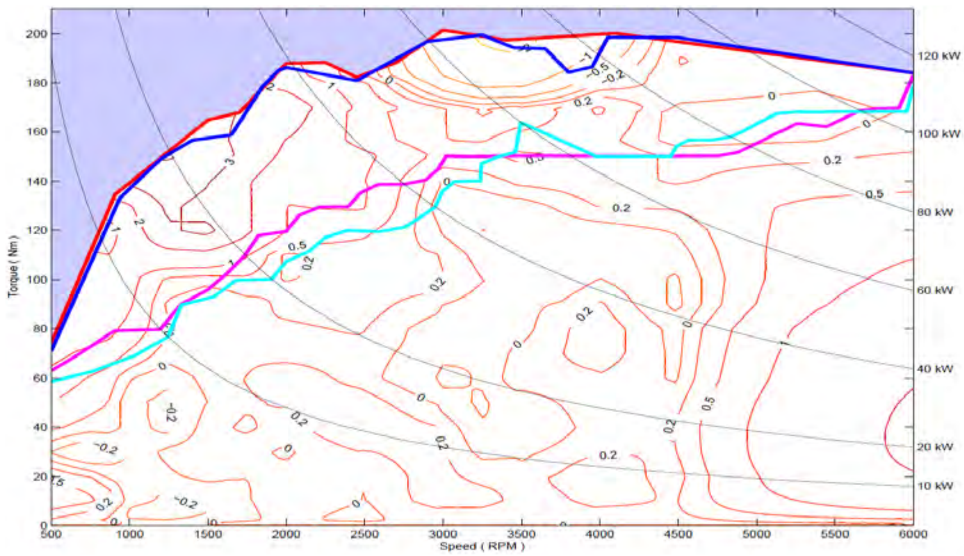


Figure 4.9 Map of the Percentage Difference in Brake Thermal Efficiency for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that the calculation of brake thermal efficiency normalizes any differences in the net energy content between the two fuels.

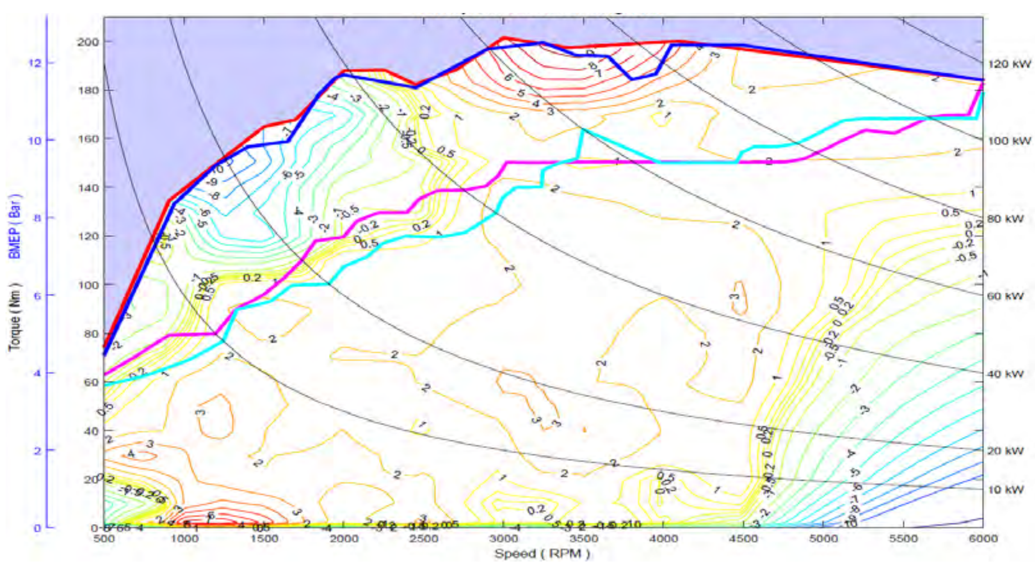


Figure 4.10 Map of the Percentage Difference in CO2 Emissions for A MY2014 Mazda Skyactiv-G 2.0L 4-Cylinder Engine with A 13:1 Geometric CR When Tested Using "Fuel A" (Tier 2, 93 AKI, E0) Versus "Fuel B" (LEV III, 88 AKI, E10).

Note: The maximum torque shown in red is for "Fuel A". The maximum torque shown in blue is for "Fuel B". Note that these results are not corrected for differences in the net energy content between the two fuels.

None of the EPA comparisons maps showed either absolute or percentage differences approaching the magnitude of the "difference map" provided by AAM. While AAM did not provide sufficient information to determine with any certainty which parameters are the ones that should be compared, the closest match of EPA data to the AAM "difference map" is percentage difference in mass of fuel consumed without correcting for the lower heating value (or net energy content) between the fuels. In the case of EPA's data, the magnitude of the percentage differences was approximately one-half of those in the AAM "difference map", particularly in the region of engine operation that are critical for GHG compliance over the FTP and HwFET (i.e., 750 to 3000 rpm, less than 6 bar BMEP, e.g., approximately the "City/Highway Critical Area" identified by AAM).

When comparing operation of the Mazda SKYACTIV-G engine (i.e. ATK2) on a brake-thermal-efficiency basis or after correction of percentage mass differences in fuel consumption to an equivalent energy basis, it becomes clear that there is little or no discernable difference between fuels A and B over areas of concern for regulatory testing beyond the differences in energy content between the two fuels.

Chassis Dyno Testing

Results from chassis dynamometer testing over the FTP using fuels C and D showed a decrease of just over 1 percent in combined-cycle CO_2 emissions and an increase of just under 1 percent in combined cycle fuel economy for the lower RON and lower net-energy-content Fuel D (see Table 4.2). So in the case of the Mazda SKYACTIV-G engine, CO_2 emissions are comparable or slightly lower when changing from a Tier 2 to a Tier 3 certification gasoline and MPG is slightly lower, but less than a 1 percent difference. The differences in CO_2 emissions found during chassis dynamometer testing with fuels C and D were comparable to the differences in CO_2 emissions found between fuels A and B during engine dynamometer testing, particularly over the areas of engine operation that are important for the regulatory drive cycles.

Table 4.2 Summary of CO2 Emissions and CAFE Fuel Economy for Chassis Dynamometer Testing of The MY2014 Mazda3 Equipped with A 2.0L Atkinson Cycle (13:1 Geometric CR) Engine Using a Tier 2 And A Tier 3 Certification Gasoline. Three Repeats of FTP75 (City Cycle) (Highway Cycle) And 95% Confidence Intervals Were Calculated Based Upon a Two-Sided T-Test.

	FTP (City)		HwFET (Highway)		Combined	
Fuel Used	CO_2 (g/mi) [± 95% conf. int.]	CAFE-MPG (mi/ga) [± 95% conf. int.]	CO_2 (g/mi) [± 95% conf. int.]	CAFE-MPG (mi/ga) [± 95% conf. int.]	CO_2 (g/mi) [± 95% conf. int.]	CAFE-MPG (mi/ga) [± 95% conf. int.]
Fuel C (Tier 2, E0, 93 AKI)	242.12 [1.36]	36.75 [0.21]	161.87 [0.57]	54.78 [0.20]	206.01 [0.60]	44.87 [0.08]
Fuel D (Tier 3, E10, 87 AKI)	238.57 [0.54]	36.58 [0.07]	160.32 [0.61]	54.28 [0.20]	203.36 [0.11]	44.55 [0.06]
% Difference for Fuel D	-1.47%	-0.47%	-0.95%	-0.92%	-1.29%	-0.72%
Significant at 95% Confidence?	Yes	No	Yes	Yes	Yes	Yes

While the combined-cycle differences found from chassis dynamometer testing were statistically significant, the very small difference in fuel economy was less than typical interlaboratory uncertainty during fuel economy testing (e.g. ± 2% of MPG). In the case of fuel D, the reduction in carbon content of the fuel from E10 blending approximately (or slightly more than) offsets differences due to the reduced net energy content relative to fuel C. Particularly when comparing either the EPA chassis-dynamometer drive cycle results to the region labeled "City/Highway Critical area" with the AAM/USCAR difference map, it is not clear how such results could have been reported by AAM without significant deficiencies in testing, data reduction, data interpolation, and/or modeling. Ultimately, without the underlying data, it is impossible to determine the specific sources of deficiencies in the "difference map" shared by AAM.

References

[1] *Alliance of Automobile Manufacturers Comments on Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025 (EPA-420-D-16-900, July 2016),* September 26, 2016, p. iii.

[2] Novation Analytics, *Technology Effectiveness – Phase I: Fleet-Level Assessment*, version 1.1, prepared for Alliance of Automobile Manufacturers & Association of Global Automakers, October 19, 2015.

[3] Novation Analytics, *Technology Effectiveness – Phase II: Vehicle-Level Assessment*, version 1.0, prepared for Alliance of Automobile Manufacturers & Association of Global Automakers, September 20, 2016.

[4] *Alliance Comments*, p. iii.

[5] *Alliance Comments*, p. ix.

[6] David Cooke, “Five Deceptive Tactics Automakers Are Using to Fight Fuel Economy Standards,” July 13, 2016, Union of Concerned Scientists, http://blog.ucsusa.org/dave-cooke/automakers-fuel-economy-standards.

[7] *Fleet-Level Assessment*, p. 12.

[8] *Greenhouse Gas Emissions Standards for Light-Duty Vehicles: Manufacturer Report for the 2014 Model Year*, U.S. EPA Report EPA-420- percent-15-026, December 2015.

[9] Alam Baum and Dan Luria, “Why We Believe the Auto Alliance Review of Fuel Economy Standards Misses the Mark,” July 6, 2016, Ceres, https://www.ceres.org/press/blog-posts/auto-alliance-review-misses-the-mark/.

[10] *Fleet-Level Assessment*, p.7.

[11] *Fleet-Level Assessment*, p. 78.

[12] *Alliance Comments*, p. 61.

[13] "Infiniti VC-Turbo: The world’s first production-ready variable compression ratio engine," Nissan Motor Corporation, September 29, 2016, https://newsroom.nissan-global.com/releases/infiniti-vc-turbo-the-worlds-first-production-ready-variable-compression-ratio-engine?query=vc-turbo.

[14] *Fleet-Level Assessment*, p. 13.

[15] *Alliance Comments*, p. iv.

[16] *Vehicle-Level Assessment*, pp. 8-9.

[17] *Vehicle-Level Assessment*, p. 8.

[18] *First law of thermodynamics*, Wikipedia https://en.wikipedia.org/wiki/First_law_of_thermodynamics .

[19] *Vehicle-Level Assessment,* p. 20.

[20] David Cooke, “Five Deceptive Tactics Automakers Are Using to Fight Fuel Economy Standards,” July 13, 2016, Union of Concerned Scientists, http://blog.ucsusa.org/dave-cooke/automakers-fuel-economy-standards.

[21] *Vehicle-Level Assessment*, pp. 27-28.

[22] *Vehicle-Level Assessment*, p. 20.

[23] *Vehicle-Level Assessment*, p. 28.

[24] *Vehicle-Level Assessment*, Figures 5 and 6, pp. 26 and 29.

[25] *Alliance Comments*, p. iv.

[26] *Vehicle-Level Assessment*, p. 8.

[27] *Vehicle-Level Assessment*, pp. 38-39.

[28] Thomas, J., "Vehicle Efficiency and Tractive Work: Rate of Change for the Past Decade and Accelerated Progress Required for U.S. Fuel Economy and CO_2 Regulations," *SAE Int. J. Fuels Lubr*. 9(1):290-305, 2016, doi:10.4271/2016-01-0909.

[29] *Alliance Comments*, p. 17.

[30] Thomas, J., "Drive Cycle Powertrain Efficiencies and Trends Derived from EPA Vehicle Dynamometer Results," *SAE Int. J. Passeng. Cars - Mech. Syst.* 7(4):2014, doi:10.4271/2014-01-2562.

[31] "Road Load Power, Test Weight and Inertia Weight Class Determination." FR 23921 ∫86.129-80. U.S. Environmental Protection Agency. P. 502. 4 May 1999. 10 November 2016.

[32] Backstrom, A. "Brake Drag Fundamentals," SAE Technical Paper 2011-01-2377, doi:10.4271/2011-01-2377

[33] Shevket, C., Ciulla, L., and Re, P., "Development of Low Friction and Light Weight Wheel Hub Units to Reduce both the Brake Corner Unsprung Mass and Vehicle CO_2 Emission (Part 1-Friction)," SAE Technical Paper 2010-01-1706, 2010, doi:10.4271/2010-01-1706.

[34] “Dynamometer Drive Schedules.” U.S. Environmental Protection Agency. 27 April 2016. https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules.

[35] "Environmental Protection Agency 2016. Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2016." U.S. EPA-420-R-16-010, Office of Transportation and Air Quality, November 2016.

[36] www.fueleconomy.gov.

[37] Environmental Protection Agency 2016. Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2016. U.S. EPA-420-R-16-010, Office of Transportation and Air Quality, November 2016.

[38] Environmental Protection Agency 2016. Greenhouse Gas Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2015 Model Year, Office of Transportation and Air Quality, EPA-420-R-16-014, November 2016.