Review of the Technology Costs and Effectiveness Utilized in the Proposed SAFE Rule

Final Report

Prepared for:

California Dept. of Justice
Sacramento, CA

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Washington, DC

October 2018

Biography of Report Author – K. Gopal Duleep

Mr. Duleep is President of H-D Systems, a Washington based consulting firm specializing in automotive technology, emissions and fuels. He has been involved with automotive fuel economy issues for over thirty years, for clients in the public and private sector. He has extensive experience with issues surrounding automotive technology cost analysis and is an internationally known expert on automobile fuel economy technology. Mr. Duleep has directed several studies for public and private sector clients in the US, Canada, European Union (EU), Australia and Mexico evaluating new technologies for vehicular engine and fuel combinations (including methanol, natural gas and other alternative fueled vehicles) as well as high octane fuels in the US and the EU. These studies have compared technical feasibility, economics, performance, maintenance, and air emissions impacts.

In 2007, Mr. Duleep served as the lead witness on automotive technology issues for the states of California and Vermont in their defense of the California greenhouse gas emission standards for light vehicles. The court ruled in California's favor and found Mr. Duleep's analysis more credible than those of the plaintiffs in every single area of challenge. He has been a consultant to several National Academy of Sciences Committees in their study of light vehicle fuel economy potential to 2030 and beyond. His work on fuel economy and GHG reduction technology for light-duty vehicles has been cited extensively around the world, and he has testified on transportation technology issues for the U.S. Congress during debates on the Clean Air Act and CAFE (fuel economy) standards.

Mr. Duleep has several degrees in Engineering from the University of Michigan, and also has an MBA in Finance from the Wharton School. He has published over 50 peer reviewed technical papers in scientific journals and has authored two encyclopedia articles on internal combustion engine efficiency.

The opinions and conclusions in this report are mine.

EXECUTIVE SUMMARY

Overview

In 2017, the US Federal Government announced their intention to propose new standards for vehicle Corporate Average Fuel Economy (CAFE) and vehicle greenhouse gas (GHG) emissions, which have been recently harmonized under Federal rulemakings. A new notice of proposed rulemaking (NPRM) published in August, 2018 found that holding standards constant at model year (MY) 2020 levels is the maximum feasible level for CAFE purposes, and appropriate for GHG purposes. According to the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA) - referred to in the following sections as "the agencies"- the information available today is different from the information before the agencies in 2012, and even from the information considered by EPA in 2016 and early 2017. A Proposed Regulatory Impact Analysis (PRIA) has been prepared to assess the potential and anticipated consequences of proposed and other alternative standards.

The preferred new CAFE standard for the 2021 to 2026 period is proposed to be equal to that currently set for 2020. Since the standards are a function of the vehicle footprint area, estimates of the 2020 footprint are required to translate the standard to a single number. The combined car/truck new vehicle fleet standards, based on the agencies' estimates of the mix of vehicles sold and resulting footprint, for the proposed standards are 39.6 mpg for 2020 and beyond, compared to existing standards which increase from 39.6 mpg in 2020 to 46.8 mpg for 2025 and beyond. The GHG standard is also proposed to be equal to existing 2020 levels, but has a further change to exclude air conditioning refrigerants and leakage, and nitrous oxide and methane emissions from the calculations for compliance with GHG standards after MY 2020. This change accounts for the apparent increase in the GHG standard (set in terms of carbon dioxide, CO2 emissions) from 227 g/mi in 2020 to 241 g/mi in 2021 and beyond.

H-D Systems (HDS) has been engaged by the California Department of Justice to examine and critique the agencies' technology analysis supporting the proposed standards. This report examines the issue of the **technology required and resulting cost** of compliance with the existing standards and the newly proposed standard. Compliance with future standards is based on the adoption of fuel saving technology to existing light-duty vehicles. This report first examines the estimates of fleet average retail price increases estimated in the 2012, 2016 and 2018 technology assessment studies in support of rulemakings by the agencies, as well as the fleet penetration of new technology for MY 2020/21 and MY2025 from which the retail price increases are derived. Second, this report examines the assumed costs and effectiveness of technologies that will be used to meet standards in the PRIA, as well as the underlying logic dictating their forecast adoption by auto-manufacturers. The first and second task outputs are combined to arrive at the conclusion that the PRIA in support of the proposed standard is incorrect and that the agencies' previous findings supporting the current standard have not been superseded by any recent developments.

Fleetwide Cost and Technology Penetration for Compliance with Standards

The existing 2017 to 2025 GHG standards were finalized in October 2012 along with CAFE standard through 2021. Due to legislative requirements, NHTSA could only propose augural standards for the 2022 to 2025 model years (MY) but the GHG standards and CAFE standards were coordinated to have (supposedly) similar levels of stringency. NHTSA and EPA used different models and somewhat different assumptions to estimate different per vehicle retail price increases that reflect the different statutory constraints on the two programs. In addition, the two agencies used somewhat different assumptions about technology and the markup from manufacturing cost to vehicle retail price. Because of carry forward credits that differ between the CAFÉ and GHG programs, costs in a specific model year may also not be comparable between the two as manufacturers can over-comply or under-comply with that years' CAFE and/or GHG standard. This makes the cost and penetration comparisons between programs and between model years confusing. In the following comparisons, we have attempted to control for these effects and make the comparisons at similar levels of fuel economy and GHG emissions using the same markup between cost and retail price.

- In the 2016 Technical Assessment report (TAR), the cost of meeting the MY2025 standards relative to MY2021 was estimated at about $1000 to $1100 on a retail price equivalent basis for both CAFE and GHG programs. These values were about 10% lower than equivalent values estimated in 2012 on a comparable basis. Other estimates by EPA using different retail markup factors are even lower, at $875.
- In the 2018 PRIA, agencies estimated the cost of meeting the MY2025 CAFE standard at $2650 and the cost of meeting the GHG standard at $2800 relative to MY2016. These values represent an increase in cost estimates of about 50% from previous 2012 and 2016 estimates.
- In contrast, the 2018 PRIA estimates for meeting MY2020 standards was $700 for CAFE standards and $550 for GHG standards. The costs were based on over-compliance with the MY2020 standard so that the comparison to earlier 2012 cost estimates for meeting MY2021 standards is reasonable, and are lower than the costs estimated in 2012 by about $60.

The differences in fleet technology penetration were as follows:

- For MY 2021, the PRIA shows a lower level of weight reduction, which is compensated for by higher levels turbocharged engine penetration and high CR Atkinson cycle engines. The PRIA forecasts do not differ significantly from the 2016 agencies' forecasts for the penetration of advanced transmissions, or in the penetration of electrified vehicle technologies (hybrids).
- For MY2025, the PRIA shows significant differences in both conventional technology and electrified vehicle technology penetrations to meet the existing MY2025 standards. Penetrations of turbocharged engines as well as mild and strong hybrids are much higher than those in the 2016 forecast. For example, strong hybrid technology penetration increases from 2% forecast earlier to 24% forecast in the PRIA, and total forecast hybrid penetration increases from 20% to 58%.

These findings from the fleetwide results would imply that conventional technology effectiveness have been reduced in the 2018 analysis, forcing the use of higher cost mild and strong hybrids to meet standards. The large incremental price differentials between the 2016 TAR and 2018 PRIA also imply that costs of hybrids could be much higher in the new analysis. These factors were examined in detail in the second task as summarized below.

Detailed Analysis of Modeled Technology Costs and Effectiveness in the PRIA

Detailed analysis of the **costs** of technologies used to meet the 2021 and 2025 standards under the 2018 PRIA show that the costs of conventional technologies (i.e., non-electric) are very similar to earlier estimates for most (but not all) technologies. Costs are significantly higher in the PRIA for mass reduction and the second generation high-compression ratio (HCR2) engine compared to those from the 2016 TAR. The costs of mass reduction are inconsistent with estimates from NHTSA and EPA sponsored studies, while the costs of the HCR2 engine may have been based on incorrect assumptions about complex exhaust system requirements. For example, the 2018 Toyota Camry has an HCR2 engine and does not use a complex exhaust system. The sources of new cost data are not documented in the PRIA.

Costs in the PRIA for all hybrid technology are higher by a factor of 2 to 2.5 in calendar year 2016, the baseline year, compared to earlier estimates (costs differentials come down in future years). This large cost increase cannot be substantiated because hybrids of all types have been in the market for a decade or more and costs have been estimated for all hybrids based on actual teardown studies[1] sponsored by EPA and the European Union. Cost data has also been publicly discussed by suppliers of hybrid systems and costs can be estimated from actual retail prices of available hybrid vehicles. The teardown studies cost data, the supplier data and the

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[1] Teardown studies refer to method of cost estimation where the vehicle is completely dis-assembled and the cost of each part estimated.

retail price data provide mostly consistent estimates of hybrid system costs that contradict the new estimates of cost.

The **effectiveness** of several conventional technologies have been reduced, while other low-cost conventional technology has been arbitrarily excluded from the forecast in the PRIA. An examination of conventional technologies whose effectiveness have been reduced in the new analysis show modeling assumptions that are not supported by available data. For instance, the estimates of mass reduction are assumed to apply to only the glider part of the vehicle (i.e., the vehicle without an engine and transmission) and the weight of the powertrain is excluded from mass reduction in many cases. In addition, the glider is assumed to account for only half the curb weight of the vehicle. Data from EPA and NHTA's own studies show that the glider weight is ~80% of the curb weight, and the weight of the powertrain scales with the weight of the glider. As a result, the impact of weight reduction is reduced and additional hybrid technology is required to achieve standards. The table below summarizes the extent of reduction in effectiveness from conventional technologies in the 2018 PRIA analysis compared to previous estimates documented by EPA, NAS, and data from actual vehicle tests conducted by EPA:

Technology Identifier		PRIA Effectiveness Estimate*	Correct Estimate*	Justification for correct estimate
Stop-start Systems		1.8%	2.8 - 3.3%	From EPA vehicle test data
48V Mild Hybrid		5.35%	9.0%	From EPA vehicle test data
Advanced 8/9 spd. Trans.		7.6 to 8%	10 to 11%	EPA Data from FCA models
Aero Drag 20% reduction		3.0%	4.3%	No Gear/Axle ratio adjustment in PRIA analysis
Tire RRC 20% reduction		3.1%	4.4%	No Gear/Axle ratio adjustment in PRIA analysis
Mass Reduction 5		6.9%	10.4%	Glider weight assumption error
Tire RRC 30% reduction		Not used	1.8%	Tires w/RRC <0.065 already available
HCR2		Not used	~19%	From 2018 Camry data
Miller Cycle		Not used	4 to 5% over Turbo	From VW/Honda data
ADEAC + 48V Hybrid		Not used	~20%	Tula Technologies/ Delphi data

*Effectiveness relative to average 2016 vehicle with 4-valve PFI engine with VVT and 6-speed automatic, tire RRC-0.09

The PRIA's costs for meeting 2021 standards are similar to earlier estimates because the standard can be attained in both analyses primarily with the use of conventional technologies whose costs have not been changed significantly in the agencies' new analysis. The $60 reduction in cost in the new analysis appears to be largely due to (inadvertent?) omission of the costs of engine friction reduction which are included in the effectiveness but not the costs, based upon detailed comparisons of costs and benefits in the 2018 PRIA to those in the 2016 TAR. The PRIA's costs of meeting 2025 standards are much higher because (1) more hybrid technology is required to meet the standard partly as a result of decreased effectiveness from conventional technology and (2) because the cost of hybrid technology is also much higher.

While the differences in the assumed technology costs and effectiveness account for much of the difference between earlier analyses and the new analysis, there are a number of incorrect assumptions in the Volpe CAFE model's baseline, and in the model logic for when technology can be adopted, which also increase costs of compliance.

The **baseline** estimates of technology penetration are not reconciled across manufacturers so that two manufacturers that have technologically identical products but with significantly different baseline fuel economy have very different compliance cost. The model assumes that all manufacturers are equally adept at integrating new technology to maximize fuel economy but this is not the case in reality. In the model, the baseline differences in fuel economy are carried for all future years and this exaggerates the differences in technology adoption requirements and costs between manufacturers.

The **CAFE model logic constrains most technology introduction** to years when the entire vehicle is being redesigned or refreshed. The actual data on technology introductions in the market show that no such constraint exists in the real world. In addition, the CAFE model also has complex rules on engine and transmission adoption and how they propagate through different vehicle models in the fleet of a specific manufacturer. These rules are not supported by any actual data and it is not clear how they are implemented for Asian or European manufacturers whose model lines are sold globally. These assumptions result in unnecessary distortion in technology paths and may bias results of costs for different manufacturers.

Finally, the PRIA utilizes an example of a Chevy Equinox small SUV to illustrate the technology adoption path and cost of meeting 2025 standards. The vehicle has a fuel economy of 34.1 mpg in 2016 and the PRIA forecast for 2025 shows the Equinox attains a fuel economy of 52.3 mpg for a cost of $5020, to slightly exceed the 2025 standard for that vehicle of 51.7mpg. Calculations using the publicly available EPA lumped parameter model (which was used to support the 2016 rulemaking) and 2016 TAR cost data show that the same technology assumptions should actually lead to a fuel economy of 57.55 mpg for a cost $4035. Removing the least cost-effective technology to closely match the PRIA forecast of 52.3 mpg, results in an estimate of attaining 52.2 mpg for a cost of $2110, which is less than half the cost estimated in the PRIA. This example illustrates how the different technology assumptions can combine to reach widely different conclusions.

The findings of this analysis are that, in the PRIA,

1) the **effectiveness** of many conventional technologies has been unjustifiably reduced or ignored
2) the **costs** of Hybrids, HCR2 engines and Mass Reduction have been unjustifiably increased.
3) Correction of these erroneous assumptions, and modifications to the CAFE model's incorrect logic on technology adoption requirements, will result in very different estimates of the cost-effectiveness of the existing 2025 standards.
4) If more correct and well supported estimates are used, the cost difference between current and proposed standards will be much lower.

Based on this analysis, HDS concludes that the estimates in the 2016 TAR on technology cost and effectiveness still represent the correct estimates based on the latest available data.

TABLE OF CONTENTS

1. INTRODUCTION

In 2017, the US Federal Government announced their intention to propose new standards for light vehicle Corporate Average Fuel Economy (CAFE)and vehicle greenhouse gas (GHG) emissions, stating that new information and analysis led to the tentative conclusion that the standards for 2025 were inappropriate. A new notice of proposed rulemaking (NPRM) published in August,2018 found that holding standards constant at MY 2020 levels is the maximum feasible level for CAFE purposes, and appropriate for GHG purposes. According to the National Highway Traffic Safety Administration (NHTSA) and the Environmental Protection Agency (EPA), hereinafter referred to as the "agencies", the information available today is different from the information before the agencies in 2012, and even from the information considered by EPA in 2016 and early 2017. A Proposed Regulatory Impact Analysis (PRIA) has been published and it assesses the potential and anticipated consequences of proposed and alternative Corporate Average Fuel Economy (CAFE) standards and carbon dioxide (CO_2) standards for passenger cars and light trucks for model years (MY) 2021 through 2026. NHTSA proposes to revise the existing CAFE standards for MY 2021 and proposes new standards for MYs 2022-2026. EPA proposes to revise the existing GHG standards for MYs 2021-2025, and proposes new standards for MY 2026.

The PRIA examined the costs and effectiveness of setting fuel economy and GHG standards for passenger cars and light trucks that change at a variety of different rates during those model years. This report discusses only the agencies' "preferred" alternative. The baseline for the analysis were the so-called augural standards that were finalized in 2016, with the further assumption that the 2025 standard remains unchanged for 2026. The preferred new CAFE standard is set for the 2021 to 2026 period to be equal to that for 2020. Since the standards are a function of the footprint area, estimates of the 2020 footprint are required to translate the standard to a single number. The combined car/truck new vehicle fleet standards, based on the agencies' estimates of the mix of vehicles sold and resulting footprint, for the proposed and existing standards are shown in Table 1-1 below.

The GHG standard is also set at 2020 levels, but has a further change to exclude air conditioning refrigerants and leakage, and nitrous oxide and methane emissions for compliance with GHG standards (expressed as CO2) after MY 2020 which accounts for the apparent increase in the standard from 227 g/mi in 2020 to 241 g/mi in 2021. Based on the agencies' forecast of the fleet mix, the standards have been determined to be 43.7 mpg for cars, 31.3 mpg for trucks and 37.0 for the fleet over the entire 2020 to 2026 period. However, the analysis estimates that manufacturers will voluntarily overshoot the standards so that the new vehicle fleet will be actually at 43.9 mpg for cars in 2020 increasing to 46.5 mpg in 2026 for cars, and the light truck fleet will be at 31.6 mpg in 2020 increasing to 33.5 mpg in 2026. The Agencies have claimed that the proposed standards will result in substantial cost savings for the consumer.

Table 1-1: Fuel Economy/CO2 Emission Standards under Current and Proposed Regulations

Model Year	Existing Standards		Proposed Standards	
	CAFE	CO2	CAFE	CO2
2017	34.0	254	34.0	254
2020	36.9	227	36.9	227
2021	39.0	212	36.9	241
2025	46.8	175	37.0	240
2026	46.8	175	37.0	240

This report examines the **costs and effectiveness of technologies** that will be required for compliance with the augural standards and the newly proposed standard. This report first examines the estimates of fleet average retail price increases estimated in the 2012, 2016 and 2018 studies by the agencies, as well as the fleet penetration of technology for MY 2020/21 and MY2025 from which the retail price increases are derived. Second, this report examines the assumed costs and effectiveness of technologies that will be used to meet standards, as well as the underlying logic dictating their forecast adoption by auto-manufacturers.

The analysis relies extensively on three reports issued jointly by EPA and NHTSA

- The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Year2021 – 2026 Passenger Cars and Light Trucks, Preliminary Regulatory Impact Analysis, July 2018
- Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Years 2022-2025, Draft Technical Assessment Report, July 2016
- Final Rulemaking for 2017-2025 Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards, Joint Technical Support Document, August 2012

The reports are referred to as the 2018 PRIA, the 2016 TAR and the 2012 TSD respectively in this report.

Section 2 documents the different estimates of cost of compliance for the entire new vehicle fleet from the three different reports. Section 3 documents the individual technology costs and effectiveness from which the estimates of fleet costs and penetrations detailed in Section 2 are derived. Section 4 describes the modeling methodology employed that justifies the technology penetration in the 2018 PRIA and provides a detailed critique of the methodology and assumptions employed. The conclusions in Section 5 are based on both parts of the analysis and summarizes the key findings from this analysis.

2. **DOCUMENTATION OF AGENCIES' FLEET TECHNOLOGY PENETRATION AND RETAIL PRICE INCREASE ESTIMATES**

2.1 Background

The 2017 to 2025 GHG standards were finalized in October 2012 along with NHTSA's CAFE standard through 2021. Due to legislative requirements, NHTSA could only propose augural standards for the 2022 to 2025 model years but the GHG standards and CAFE standards were coordinated to similar (but not exactly identical) levels of stringency. NHTSA and EPA used different models and somewhat different assumptions to estimate the per vehicle retail price increases that reflect the different statutory constraints on the two programs. This section documents the different estimates developed by EPA and NHTSA over the 2012 to 2018 period for meeting the existing standards to MY 2025. The discussion is made complex and confusing because

- EPA and NHTSA use different markup factors to convert cost to retail price but EPA has harmonized the factors in only the 2012 analysis
- The baseline year for fleet projections have changed over the years and EPA and NHTSA have used different baseline years in their analyses. This affects the model mix forecast as well as the car/ truck split of the fleet.
- The credit carry-forward and carry-back provisions have been modeled by NHTSA resulting in over compliance in some years and under compliance in others in their forecast. EPA has not modeled this effect and their forecasts are for compliance in each year.
- EPA includes the effect of battery electric and plug-in hybrid vehicle sales forced by California's Zero Emission Vehicle (ZEV) mandate but NHTSA does not. Since the ZEV compliant vehicles have very high fuel economy, EPA's cost of meeting standards should be lower than those developed by NHTSA, other factors held constant.

The retail price increase estimates developed in 2012 and 2016 by the two agencies relied on the same estimates of individual technology improvements' costs and effectiveness. In addition, NHTSA and EPA had traditionally used different methods to calculate overhead costs with NHTSA using a constant multiplier of 1.5 for all technologies to generate a Retail Price Equivalent (RPE) while EPA used different markups depending on technology complexity to develop Indirect Cost Multipliers (ICM). For the 2012 analysis, EPA changed several of the ICM factors to produce results similar to the NHTSA RPE. The first change was to normalize the ICM values to be consistent with the historical average retail price equivalent (RPE) of 1.5, by applying a factor of .5/.46 to all indirect cost elements. The second change was to re-consider the markup factors and the data used to generate them. The result was to increase the markup in all cases. The final change is the way in which the ICM factors are applied. In previous analyses ICMs were applied to the learned value of direct costs. However, since learning influences direct costs only, the agencies were concerned that this could overstate the impact of learning on total costs. Since 2012, indirect costs are established based on the initial value of direct costs and held constant until the long-term ICM is applied.

2.2 Retail Price Increase from 2012 Analysis

The retail price increase due to complying with standards are different for vehicles of different sizes and body styles (e.g., pickup, sedan, SUV), as well as the level of technology adoption in the baseline year from which cost increments are projected. The 2012 TSD used MY2008 as the baseline year for estimating the mix of vehicles sold by model, manufacturer, size and body style in model years 2017 to 2025. (NHTSA also performed analyses using a 2010 baseline and the results were modestly different from the one using the 2008 baseline). The EPA and NHTSA results for the car and truck fleets are shown for select years in Table 2-1. Retail price increases are relative to 2016 technology levels and costs. The combined result assumes a car/truck mix of 67%/33%.

Table 2-1: Retail Price Increases from 2012 TSD for Compliance with MY2017-2025 Standard

Model Year	NHTSA			EPA		
	Car	Light Truck	Combined	Car	Light Truck	Combined
2017	$208	$87	$164	$208	$57	$154
2020	$837	$470	$709	$634	$415	$557
2021	$1034	$648	$900	$767	$763	$766
2025	$1577	$1040	$1400	$1726	$2059	$1836

As can be seen in Table 2-1, EPA showed substantially higher costs for 2025 especially for light trucks. The average car + light truck cost in 2025 was estimated by NHTSA to be $1400 and by EPA to be $1836, a $436 difference. The agencies analysis showed that NHTSA's model allowed multi-year planning to take advantage of carry-forward credits so that costs in earlier years were higher but allowed 2025 compliance with lower fuel economy and lower cost than implied by the standard, while EPA's model forced year by year compliance. This accounted for $247 of the cost difference. Second, NHTSA's model allowed manufacturers facing high costs to pay the fine rather than comply while EPA does not, since the GHG regulations does not allow civil penalties for non-compliance. This explained $120 of the difference. The final difference of about $70 was attributed to EPA including the cost of changing refrigerants in the air-conditioner, which affects GHG emissions but is not included in the CAFE standard.

2.3 Costs from 2016 Mid-Term Evaluation TAR

In 2016, EPA and NHTSA published a mid-term evaluation of the standards and used a different baseline (actual MY2014 for EPA and a mid-model year 2015 estimate for NHTSA) than the 2012 analyses so that the mix of vehicles changed significantly for the projections. In particular, the car- truck mix changed from 67/33 to 52/48 percent and other changes also were included on vehicle model and manufacturer mix, but the markup differences between ICM and RPE approaches were **not** reconciled. In order to facilitate comparisons to the 2012 analysis, the RPE based estimates are shown from the 2016 draft TAR which provided estimates using both ICM and RPE approached. Costs are relative to the 2021 model year since only the MY 2022 to 2025 standards were being reconsidered and the combined cost (in 2013 dollars) for the 52/48 mix was recalculated for the 2012 analysis to place it on a comparable basis. Since NHTSA's model uses credit carry-forward to comply with the MY2025 standard, the MY2028 cost was used as an indicator of the stabilized long-term cost of meeting the standard. Note that the issue of refrigerant cost does not enter the analysis since it is expected that the refrigerants will be fully phased in by 2021.

Table 2-2: Retail Price Increase from MY2021 to MY2025 Forecast by Different Studies (in 2013 $)

	Car	Truck	Combined
EPA 2012	1024*	1384*	1197* (new mix)
EPA 2016 RPE case	789	1267	1017
NHTSA 2012	580*	419*	502* (new mix)
NHTSA 2016	1207	1289	1096

Source: Draft 2016 TAR *adjusted to 2013$ using the GDP deflator of 0.9366

The 2016 retail price increase estimates from NHTSA and EPA for complying with the MY2025 standard are somewhat different but these differences arise from issues related to accounting for the California ZEV mandate as well as other statutory differences discussed earlier. The low value of the incremental retail price between MY2021 and MY2025 forecast by NHTSA in 2012 was partially due to overcompliance in MY2021 and undercompliance in MY2025 which could account for about $350 of the $594 difference between the 2012 and 2016 estimate. However, the estimates by EPA in 2012 for MY2025 are higher than those in 2016 by $180 due to the emergence of new, cheaper technologies. The EPA 2016 estimate for MY2025 is also consistent with the NHTSA estimate for MY2028, with much of the $79 difference between the two estimates due to EPA inclusion of plug-in hybrids and electric vehicles forced by the California ZEV mandate at zero cost. It should be noted that the EPA approach using ICM yields an even lower retail price increase for MY2025 of $894. This was revised to $875 in the final TAR, which used an updated actual 2015 baseline and other minor cost revisions relative to the draft TAR. The final documents for the TSD and the Proposed Determination in 2016 do not explicitly model the CAFE program and provide cost of compliance only for GHG regulations.

2.4 Costs from the 2018 PRIA

Retail price increases for compliance with the existing standards and the newly proposed standards which hold standards constant at 2020 levels over the 2021-2026 period have been re-estimated in the new Preliminary Regulatory Analysis (PRIA) published in 2018. In the new analysis, the fleet composition changes as a function of standards so the cost comparisons are not completely comparable between cases. The retail price increases for select years for the combined car + light truck fleet (separate retail price increases for each fleet are unpublished) are shown in Table 2-3 (in 2016$) for the 2017 to 2028 period, relative to a 2016 baseline under the existing and new standards. The new calculations show a dramatic change in retail price increases associated with meeting the existing MY2025 standard, climbing from $1400 estimated by NHTSA in 2012 to $2650. In addition, the retail price increases jump by $600 in a single year between MY2020 and MY2021 that distort comparisons with earlier estimates on the cost increase between 2021 and 2025. This is because the manufacturers are projected to exceed the standard by 2.5 mpg in 2020 and by 3.4 mpg in 2021 in the new forecast.

Table 2-3: Retail Price Increases and Attained MPG from the 2018 PRIA- CAFE Case

		2017	2020	2021	2025	2028
Existing Standard $		$250	$1400	$2000	$2650	$2650
MPG attained.		33.9	39.4	42.4	45.7	46.4
Proposed Standard $		$150	$600	$650	$700	$700
MPG attained		33.7	37.2	38.3	39.2	39.6

Source: Tables 7-2, 7-4 in the 2018 PRIA

From table 2-3, the retail price increase estimated by NHTSA between MY2016 and 2021 is only $650 compared to the $1100 estimated previously but the increase from 2020 to 2025 is $1250. In contrast, the retail price increases due to meeting the proposed standard (which holds 2020 standards constant over the 2021-2028 period) are quite similar to earlier estimates, and the standards are exceeded by 0.3 mpg in 2020 and by 1.4 mpg in 2021. In this case the MPG attained in 2025 is quite similar to the MPG attained under the existing standards case in 2020, but for half the cost.

The costs for meeting the GHG standards are shown below and it appears that the costs of low GHG refrigerants are not included, and the effects of the ZEV mandate also excluded in the 2018 analysis. The dramatic change in retail price increase between MY2020 and MY 2021 is not forecast in this analysis, although the overall MY 2028 retail price increase for meeting CO2 standards is comparable to the $2650 forecast for meeting CAFE standards. The over-compliance in 2020 and 2021 is not large unlike the CAFE case, which would affect the 2020 and 2021 price increases

Table 2-4: Retail Price Increases and Attained MPG from the 2018 PRIA- GHG Case.

GHG Standards		2017	2020	2021	2025	2028
Existing Standard		$200	$1200	$1650	$2350	$2800
CO2 achieved g/mi		251	213	198	182	175
Proposed Standard		$100	$400	$450	$500	$550
CO2 achieved g/mi		252	228	236	232	230

Source: Tables 7-23, 7-25 in the 2018 PRIA

Under proposed standards which are flat beyond MY 2020, the retail price increases for each year in the MY 2017 to 2020 period are significantly lower in the new forecast than those computed in 2012.

Since the pathways are different for meeting the existing vs. proposed standards, it is informative to compare the costs associated with the same level of fuel economy increase. Figure 2-1 compares the cost relative to the actual increase in MPG relative to the 2016 base year where the fleet actual CAFÉ was 32.2 MPG. It can be seen that the costs for a 5 to 7 mpg increase from 2016 are substantially higher on the existing standards pathway relative to the pathway for the proposed standard, by about 30% to 40%. The PRIA does not make it clear why the costs on the two pathways are so different. While attaining standards a little later in time can yield savings due to learning, these effects are quite modest in the order of a few percent in 2 to 3 years, and would not explain much of the cost difference between the two pathways. This suggests that cost ineffective technologies are included in the existing standards compliance pathway. Comparing the NHTSA analysis for meeting existing standards from the 2016 draft TAR and the 2018 analysis shows a sharp divergence in costs starting in 2019 as shown in Figure 2-2. The two results point to the possibility that in the 2018 analysis, NHTSA has increased the costs of least cost-effective technologies (typically hybrids and electric vehicles) and also brings them in early to increase costs in 2020 and 2021. These issues are explored in detail in Section 3 of this report.

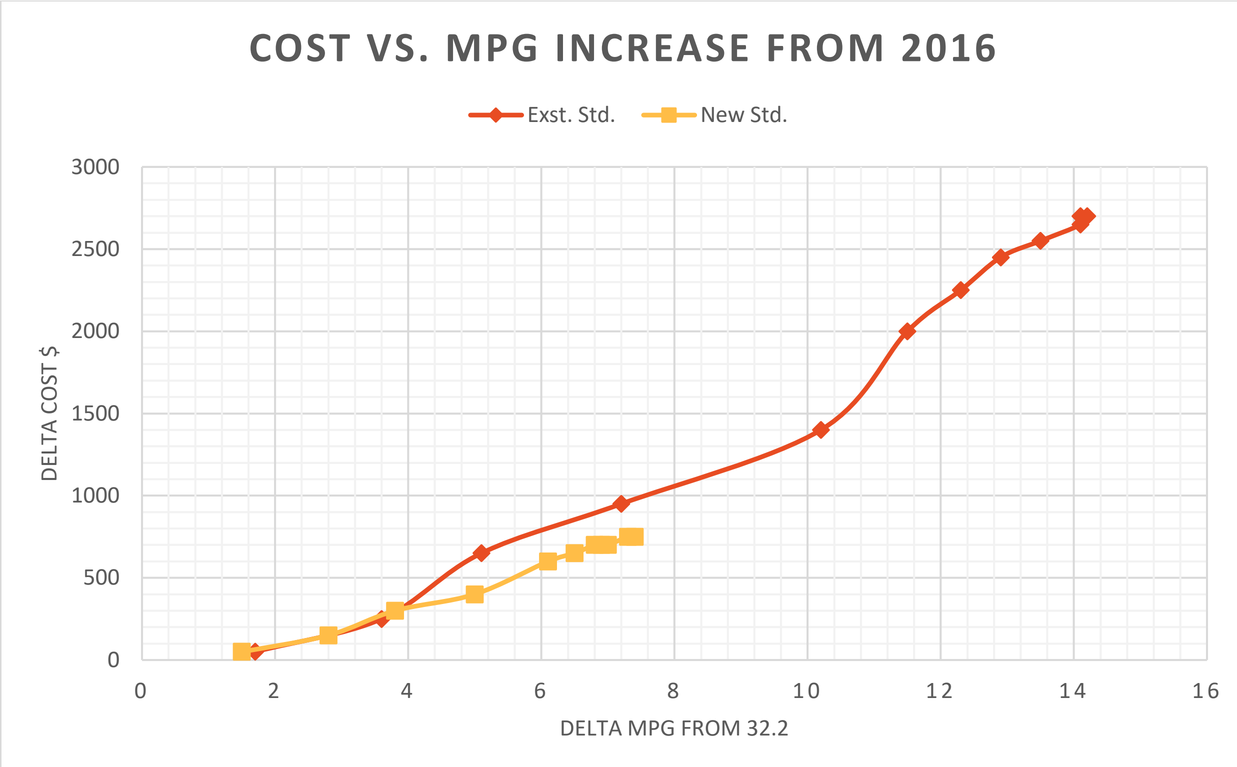

Figure 2-1: Cost vs. Fuel Economy Increase from 2016

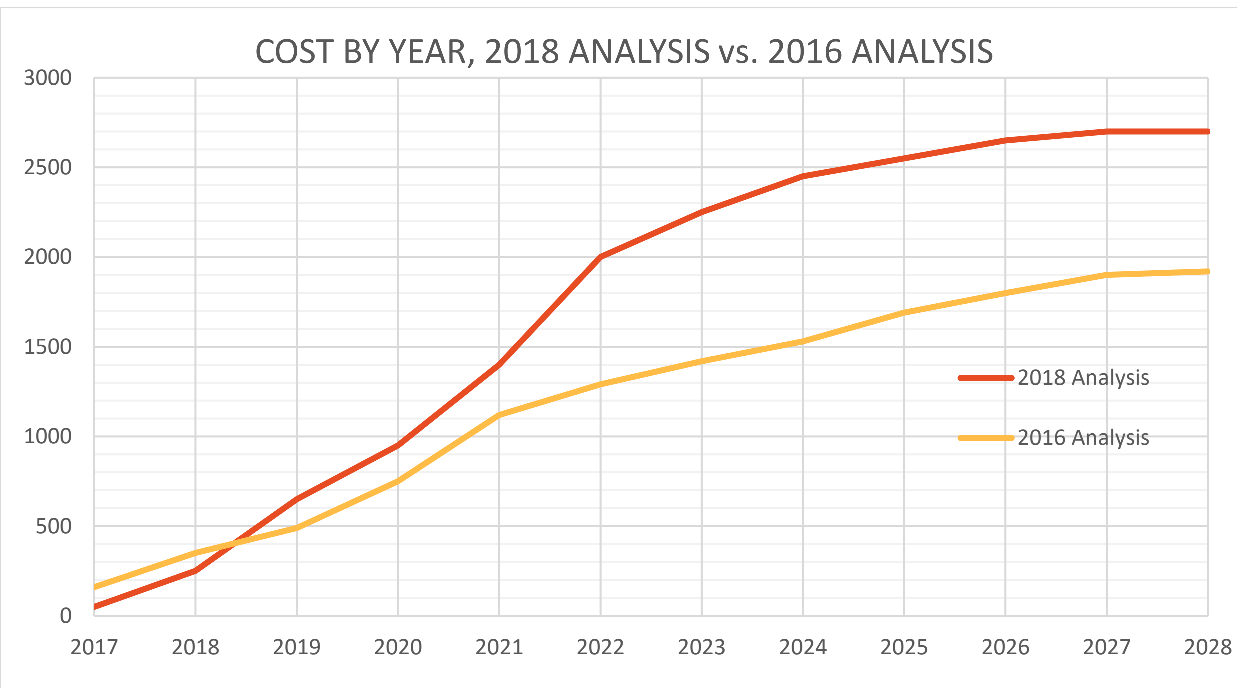

Figure 2-2: Incremental Retail Price by Year to meet Current Fuel Economy Standards

Based on a comparison of the fleetwide retail price increases forecast, the following conclusions are reached

- The PRIA forecast for meeting existing CAFE standards shows significant over-compliance of standards in MY 2020-2021 that appears unrealistic as this has never happened historically, and results in very large retail price increases.
- Under proposed standards, the standards for MY 2020 (which are identical to those in the existing standard) are met with a retail price increase of $650 that is less than half of what is forecast under existing standards. This price increase is **lower than the $789 forecast for meeting existing MY 2020 standards** in the 2016 TAR.
- In contrast**, the price increases forecast for meeting existing MY 2025 standards are substantially higher in the new forecast at $2800** compared to the $1665 forecast by EPA in 2012 TSD. This higher price results in an even higher differential between prices to meet existing versus proposed standards.
- The very large differential in costs associated with a relatively small delay in meeting the same levels of fuel economy and CO2 fleetwide between the existing and proposed standards show that the forecasting model has errors in the conceptual framework and technology adoption pathways specified.

Details of the technology pathways under the existing and proposed standards are investigated in more detail below.

2.5 Technology Adoption to meet 2020 and 2025 Standards

The technology adoption paths that underlie the cost and retail price impacts described above have also been quite variable between the analysis from different years and even between the CAFÉ and GHG analyses in the same year. In addition, the list of technologies considered have changed over the years although the 2016 and 2018 analyses use a near identical list. In addition, the nomenclature and grouping of technologies differ between EPA and NHTSA so that a complete comparison between the two agencies' forecasts are made more difficult. In addition, the EPA itself issued two different forecasts in 2016, one in the draft Technical Assessment Report (TAR) and a second in the Final TAR that differed in some technology penetrations significantly[2]. The volatility of the technology penetration projections suggest that subjective inputs on technology, and sensitivity of the technology adoption algorithms in the model to small changes in technology costs and effectiveness can make the forecasts vary significantly. Another factor affecting the technology forecasts for a particular model year is the

[2] The difference between the draft and final TAR technology penetration was largely due to manufacturer comments that the HCR2 engine technology may not be widely available for adoption by 2025.

use of carry forward and carry back credits, which are modeled differently for the CAFE and GHG program.

The technology penetration comparisons in Table 2-5 compare the 2016 draft TAR, 2016 final TAR projections for GHG, 2016 draft TAR projection for CAFE and the 2018 PRIA forecast for CAFÉ and GHG (The final 2016 TAR does not include a CAFE based forecast). In the case of the 2018 analysis, the projections show that both CAFE and compliance targets are exceeded for the proposed standard so we have compared the MY2021 penetration forecasts from the 2016 and 2018 analysis. For the existing standards case, we have compared the MY2028 penetrations since the 2025 standard is not met without credits until 2028 in the new analysis. These place the CO_2 and MPG values attained in the model year compared to be nearly identical across the different projections.

Table 2-5: Comparison of Technology Penetration in MY 2021 Fleet from Agency Studies

	2016 DRAFT TAR CAFE	2016 DRAFT TAR GHG	2016 FINAL TAR GHG	2018 PRIA GHG	2018 PRIA CAFE
WEIGHT REDUCTION	5.2	7	7	3.3	3.3
TURBO 18 BAR	20	24	24	31	39
TURBO 24 BAR	4	1	1		
HIGH CR	2	6	6	12	16
TURBO MILLER	0	0	0	NA	NA
8+ SPEED AUTO.	40	90	90	91	92
ADVANCED CVT	18				
IDLE STOP-START	21	14	14	11	13
MILD HYBRID	8	3	3	1	0
STRONG HYBRID	6	2	2	2	2
PLUG-IN HYBRID	0.5	2	2	0	0
BATTERY ELEC.	1	2	2	1	1

Table 2-5 shows the technology penetration in the MY 2021 new vehicle fleet from different studies. The 2018 PRIA data show a lower level of weight reduction, which is compensated for by significantly higher levels turbocharged engine penetration and HCR1 engines. The 2018 forecasts do not differ significantly from the 2016 forecasts for the penetration of advanced transmissions, or in the penetration of electrified vehicle technologies (hybrids). The need for higher penetration levels of conventional engine technologies to meet the 2020/21 standards suggest that the effectiveness for these technologies were reduced, but since fleet costs remain comparable, the cost estimate for each technology could not be significantly different for conventional technology than the cost estimate from the 2016 studies.

The comparisons for MY2025, however, show significant differences for both conventional technology and electrified vehicle technology penetrations to meet the current MY2025 standards. The 2016 analysis did not utilize Dynamic Cylinder Deactivation in their list of compliance technology, but it can be seen in Table 2-6 that penetrations of turbocharged engines as well as mild and strong hybrids are much higher than those in the 2016 forecast. (Since strong hybrids use an electric CVT transmission, the higher penetration of strong hybrids would explain the lower projected use of advanced transmissions). This would suggest that conventional technology effectiveness have been reduced in the 2018 analysis, forcing the use of higher cost mild and strong hybrids to meet standards. The large RPE differentials between the 2016 and 2018 analyses also suggest that costs of hybrids could be much higher in the new analysis. These results provide guidance on the specific topics for focus in the analysis of individual technology costs and effectiveness estimates.

Table 2-6: Comparison of Technology Penetration in MY 2025 Fleet from Agency Studies

	2016 DRAFT TAR CAFE	2016 DRAFT TAR GHG	2016 FINAL TAR GHG	2018 PRIA GHG	2018 PRIA CAFE
WEIGHT REDUCTION	15	6.6	9	7.3	6.4
DYNAMIC DEAC.	NA	NA	NA	4	6
TURBO 18 BAR	13	22	27	62	64
TURBO 24 BAR	14	11	7		
HIGH CR	0	44	27	26	26
TURBO MILLER	0	4	2	NA	NA
8+ SPEED AUTO.	51	90	93	76	72
ADVANCED CVT	18				
IDLE STOP-START	38	20	15	15	14
MILD HYBRID	13	18	18	38	32
STRONG HYBRID	14	2.6	2	20	24
PLUG-IN HYBRID	0.5	1.7	2	1	1
BATTERY ELEC.	1	2.6	3	1	1

2.6 Findings

The analysis of fleet costs and fleet technology penetration from the 2012 TSD, the 2016 TAR and the 2018 PRIA show the following:

- The costs of compliance with CAFE regulations is different from those for the GHG program partly due to differences between the two programs' requirements and partly due to the use of different multipliers to convert manufacturing cost to retail price equivalent.
- Because of carry forward credits that differ between the CAFE and GHG programs, costs in a specific model year may not be comparable as manufacturers can over-comply or under-comply with that years' CAFE and/or GHG standard
- In the 2012 TSD, the cost of meeting MY2025 standards relative to a MY2016 baseline was estimated at $1400 for the CAFE program and $1836 for the GHG program
- In the 2016 TAR, the cost of meeting the MY2025 standards relative to MY2021 was estimated at about $1000 to $1100 for both CAFE and GHG programs. (EPA estimated a lower price of $875 using a lower cost to price markup). These values were about 10% lower than equivalent values estimated in the 2012 TSD when placed on a comparable basis.
- In the 2018 PRIA, the cost of meeting the MY2025 CAFE standard was estimated at $2650 and the cost of meeting the GHG standard at $2800. These values represent an increase in cost estimates of about 50% from previous 2012 and 2016 estimates.
- In contrast, the 2018 PRIA estimates for meeting MY2020 standards was $700 for CAFE standards and $550 for GHG standards. The costs were based on over-compliance with the MY2020 standard so that the comparison to earlier estimates for meeting MY2021 standards is reasonable and are lower than the costs estimated in 2012 by about $70.

The differences in fleet technology penetration were as follows:

- For MY 2021, the 2018 PRIA shows a lower level of weight reduction, which is compensated for by higher levels turbocharged engine penetration and HCR1 engines. The PRIA forecasts do not differ significantly from the 2016 forecasts for the penetration of advanced transmissions, or in the penetration of electrified vehicle technologies (hybrids).

- For MY2025, the PRIA shows significant differences in both conventional technology and electrified vehicle technology penetrations to meet the existing MY2025 standards. Penetrations of turbocharged engines as well as mild and strong hybrids are much higher than those in the 2016 forecast. For example, strong hybrid technology penetration increases from 2% forecast in the 2016 TSD to 24% forecast in the 2018 PRIA, and total hybrid penetration increases from 20% to 58%.

3. DOCUMENTATION OF TECHNOLOGY SPECIFIC COSTS AND EFFECTIVENESS

3.1 Overview

The method by which manufacturers comply with future CAFE or GHG standards is by adding technologies to their fleet to make them more fuel efficient and reduce GHG emissions, rather than by making vehicles of different sizes or less powerful in general. Regulatory agencies have traditionally modeled future fuel economy potential by keeping the size and performance of individual vehicle models approximately constant to forecast fuel economy as a result of technology adoption, and separately projecting the sales mix of models based on future fuel price and consumer taste expectations. The sales mix projections have historically not been accurate as both fuel price and consumer preferences have been difficult to forecast, and mix projections from the regulatory agencies over the years have varied significantly. In addition, manufacturers have phased out some models while introducing new model types but the regulatory agencies have typically kept the list of vehicle models constant over the forecast period or, in some instances, added or deleted vehicle models if this was known at the year the forecast was made. This section examines only the costs and effectiveness of technology as distinct from their application to specific models and does not examine the changes in the sales forecast which also affects future fleet CAFE and GHG emissions.

Technology improvements are generally considered relative to a “null” baseline corresponding approximately to the median 2010 vehicle. The list of technologies is generally well known and the majority of technologies that will be used to meet 2020 and 2025 standards have already been introduced in at least some vehicles in the new vehicle fleet as of 2018. The list of technologies can be divided into

- Conventional engine technologies
- Partial of fully electrified drivetrain technology
- Transmission technologies
- Vehicle body related technologies
- Auxiliary system technologies

Conventional engine technologies include variable valve timing (VVT) which is sometimes called cam phasing, variable valve lift (VVL), cylinder deactivation (DEAC) and gasoline direct injection (GDI). All of these technologies have been in production for over 10 years and NHTSA’s analysis labels these as “base” engine technologies, since most new engines already feature one or more of these technologies. Advanced engines include downsized turbocharged engines

(TURBO), engine with high compression ratios (CR) and the Atkinson cycle (ATK) and advanced cylinder deactivation systems (ADEAC). Turbocharged downsized engines have been in the market for about 10 years, but earlier versions had controlled turbo boost so the engine maximum brake mean effective pressure was controlled to 18 to 19 bar (TURBO18) while more recent versions have managed to increase BMEP to 23 to 24 bar (TURBO24). High compression ratio (HCR) engines, generally in the 13 to 14 compression ratio range, have been used in hybrid vehicles for over 10 years but have only recently (2014) been offered in non-hybrid vehicles. In 2018, Toyota and Honda have introduced second generation versions of these engines (HCR2) that have improved power and better efficiency for use in non-hybrid vehicles. Only engines with ADEAC technology are not yet in the market although press reports indicate the potential for introduction by GM in MY2019. Separately, low friction lubricants (LFL) and engine friction reduction (EFR) were also considered with two levels of friction reduction (EFR1 and EFR2) by the agencies in 2012 and 2016 but have been bundled in the 2018 report as LUBEFR with 3 levels that are not well described in the PRIA.

Electrified drivetrain technology have been classified into five types – the start/stop systems (S/S) that shuts the engine down at idle, the mild hybrid system typically in the form of a belt driven alternator/starter (BAS), the strong hybrid featuring high power (>40kw) electric motor(s) as typified by the Toyota Prius, the plug-in hybrid electric vehicle (PHEV) which is a strong hybrid capable of pure electric drive over most common driving conditions for a limited range and the battery electric vehicle (BEV). Forecasts from both 2016 and 2018 for compliance with existing 2025 standards show very small penetrations (>2%) for BEV and PHEV models so this section does not explore the costs and effectiveness of such vehicles. All other types of hybrids have been available in the marketplace for 10 or more years.

Transmissions of two types dominate the fleet and they are conventional automatic transmissions (AT) with gears, and the continuously variable transmission (CVT). Other types such as manual transmissions (MT) and dual clutch automated manual transmission (DCT) are also present but have low current and forecasted penetrations so they are not examined in this report. Automatic transmissions can have more gears and are recognized as 6AT, 8AT, etc denoting the number of gears while CVTs can have increased ratio spread but have been described by the agencies only as advanced CVT. In addition, the internal friction reduction has been modeled in 2 levels of reduced friction, but the grouping of gears/friction reduction levels varies between the 2012, 2016 and 2018 reports, making comparisons difficult and inexact.

Body technologies include mass (weight) reduction (MR), tire rolling resistance reduction (ROLL) and aerodynamic drag reduction (AERO). Drag and rolling resistance by 10% and 20% from baseline levels have been included in all the reports but the baseline assumptions are a little different between the 2012, 2016 and 2018 reports. Weight reduction in steps of 2.5% or 5%

have been used in the reports but they do not have the same assumptions about secondary weight reduction associated with a smaller powertrain to maintain constant performance.

Finally, other auxiliary system technologies are similarly recognized in all reports and include electric power steering (EPS), improved accessories (IACC) at two levels of improvement, low drag brakes (LDB) and secondary axle disconnect (SAX) for four-wheel drive vehicles. The comparison and costs and effectiveness for all of the above technologies are provided below.

3.2 Comparison of Technology Cost Estimates

The 2016 final TAR provided a comprehensive set of data on technology costs and was based on the extensive public review of the draft TAR data. EPA corrected some of the technology cost data based on the comments received on the draft TAR but much of the data was unchanged from the draft TAR which itself used data from the 2012 TSD as well as data from the National Academy of Sciences report published in 2015. The 2016 final TAR does not include as much detail in describing analysis details and the draft TAR is a more comprehensive source of data on technology costs and penetration. Hence, the cost data from the 2016 TAR is a composite of all of the earlier work and this data is contrasted to the cost data published in 2018 PRIA. Costs of technology in the 2016 TAR were developed by EPA and provided for discrete technologies, but the 2018 PRIA cost data was developed by NHTSA and is provided only for some discrete technologies while other cost data have been provided for technology packages. The contents of some technology packages are not clear especially with regard to engine friction reduction and in some cases, the use of VVL, and we have made assumptions on the use of these technologies for each package. In addition, since EPA and NHTSA use different methods to account for overhead cost, we have compared the direct manufacturing cost in this section except for one technology, weight reduction, where this cost comparison is inadequate.

The costs of conventional engine technologies for a four-cylinder engine are provided in Table 3-1. Some of the costs in the 2018 PRIA were derived from the package cost by subtracting out other package technology to make the 2016 and 2018 data comparable. We assume that agreement within ±5% of the average of the two numbers suggests near equivalence and on this basis, the 2018 costs for the High CR Atkinson cycle second generation engine are significantly higher in the 2018 TAR, but costs for cylinder deactivation are significantly lower. The 2018 analysis also utilized Advanced Cylinder Deactivation in its analysis but the package components were not completely explained in the PRIA.

Table 3-1: Comparison of Direct Manufacturing Cost of Conventional Engine Technologies

Technology		2016 TAR	2018 PRIA	Comment
VVT (dual cam phasing)		73	78	
VVL (continuous)		188	214	
GDI		218	237	
DEAC		85	28	
TURBO 18BAR		413	389	Derived from package
TURBO 24 BAR		248	231	Relative to TURBO18
HIGH CR ATKINSON 1		NA	213	HCR1
HIGH CR ATKINSON 2		110	317	(not used in 2018 analysis)
CEGR		240	277	Used with TURBO24
ADEAC		Not used	385?	Derived from package

Source: Tables 5-53 to 5-75 in the 2016 TAR, and Table 6-10 in the 2018 PRIA

Another technology that is not well defined in the 2018 analysis is the issue of engine friction reduction; the PRIA does list costs for friction reduction levels 1,2 and 3 as $56, $3 and $3 respectively (implying that levels 2 and 3 may be associated with lubricants due to the low absolute cost), but the use of friction reduction at any level in the technology packages is not stated. The NPRM does contain the statement "Manufacturers have already widely adopted both lubrication and friction reduction technologies. This analysis includes advanced engine maps that already assume application of low-friction lubricants and engine friction reduction technologies. Therefore, additional friction reduction is not considered in today's analysis". This implies that friction reduction may be included in the advanced engine technology packages, whereas the 2016 TAR analysis includes this technology as being available for use to improve fuel economy to 2025.

Table 3-2: Comparison of Direct Manufacturing Costs of Electrification Technologies in CY2016

Technology		2016 Final TAR	2018 PRIA	Comment
Start Stop		268 to 303	267 to 328	12V System
Mild Hybrid (BAS)		724	1340 to 1585	48V System
Strong Hybrid (P2)		2650 to 3300	4437 to 6630	P2 used for pickup
Strong Hybrid (PS)		~Equal to P2	7133 to 9658	No PS for pickup

Source: Tables 5-84,85 and 86 in the 2016 TAR, Table 6-30 in the 2018 PRIA

The costs of electrification technologies are compared in Table 3-2. Other than the start-stop system where the cost estimates are comparable, costs for the other systems generally vary by vehicle weight. The BAS system costs estimated in the 2016 TAR kept system size constant across all vehicles, while the 2018 PRIA increases system power with size. However, it is notable that 2018 PRIA estimate is approximately double the 2016 TAR estimate, and it is not clear from the discussion in the PRIA why such a large increase occurred. The difference is not explained by the difference in battery costs which was estimated at $391 in the PRIA and $314 in the TAR, explaining only $78 of the $700 difference. Cost estimates for both P2 and power split (PS) are also significantly different between the 2016 and 2018 estimates and cost estimates differ by a factor of about 2 for P2 hybrids and by a factor of 2.5 for PS hybrids. The PS hybrid cost estimates are particularly surprising since the costs have been investigated extensively since its original introduction in 1998. The 2016 TAR estimates are in line with other analyses like the NAS estimate, and also consistent with actual retail price increments observed in the market, as detailed in Section 4.

However, the TAR and PRIA have different learning curves for all electrified technology so that the costs comparison is closer for 2025 as shown below. The cost increment of the BAS hybrid falls from about $750 to about $250, while the increment for P2 and PS hybrids falls to 1.5 to 2 times the TAR based cost.

Table 3-3: Comparison of Direct Manufacturing Costs of Electrification Technologies in CY2025

Technology		2016 Final TAR	2018 PRIA	Comment
Start Stop		205 to 232	187 to 247	12V System
Mild Hybrid (BAS)		580	780 to 822	48V System
Strong Hybrid (P2)		2160 to 2650	3555 to 4878	P2 used for pickup
Strong Hybrid (PS)		~Equal to P2	5275 to 7143	No PS for pickup

Source: Tables 5-84,85,86 in the 2016 TAR, Tables 6-32,33 in the 2018 PRIA

The comparison of transmission technologies' costs is more difficult as the 2018 PRIA differs in the way it groups and designates improvements relative to the 2016 TAR. The TAR provides data for 6 speed automatics and 8 speed automatics with two levels of friction reduction relative to the base 2016 transmission. The PRIA provides data on 6, 8 and 10 speed automatics with "level 2" friction reduction and in some cases "level 3" friction reduction but it is not clear if these correspond to the two levels used by EPA. The comparison in Table 3.4 compares the TAR level 1 costs to the PRIA's "L2" costs and the TAR level 2 cost to the PRIA "L3" cost recognizing that they may not be equivalent. While the comparisons are inexact, the 8AT L2 cost appears comparable to the "TRX22" which corresponds to an 8AT with the maximum level of friction reduction in the 2016 TAR. The 2018 costs of most transmission technologies do appear to be higher than the 2016 cost data but a definitive statement is more difficult due to the inexact comparisons.

Table 3-4: Comparison of Direct Manufacturing Costs of Transmission Technologies

Transmission Type		2016 TAR	2018 PRIA	Note
6AT, Efficiency level 1		40	132	2018 PRIA L2 level may be between 2016 level 1 and 2
6AT, Efficiency level 2		280		
8AT, Efficiency Level 1		176	299	As above
8AT, Efficiency Level 2		396	464	
10 AT, Efficiency Level 1		NA	383	

Source: Table 5-81 in the 2016 TAR, Table 6-22 in the 2018 PRIA

Body technologies include aero drag reduction and rolling resistance reduction, as well as weight reduction. The 2018 PRIA has more carefully defined the absolute levels of drag, rolling resistance and mass reduction so that somewhat different levels of reduction are possible by vehicle type and starting point (2016 base vehicle). Costs for equivalent levels of reduction are compared, and the costs of drag reduction is significantly higher in the 2018 PRIA while the costs of rolling resistance reduction are identical for 10% reduction but higher in the PRIA for 20% in comparison to costs in the 2016 TAR.

Table 3.5: Comparison of Manufacturing Costs of Body Technology (Retail Price for MR)

Technology		2016 Final TAR	2018 PRIA	Comment
AERO 10%		44	92	
AERO 20%		176	230/667pickup	Higher cost for pickup
ROLL 10%		6	6	
ROLL 20%		57	42	
MR 5% ($/lb.)		-0.97	0.46	Cost saving in 2016
MR 10% ($/lb.)		-0.075 (0.82)	0.85 (1.24)	Marginal cost in ()
MR 15% ($/lb.)		0.53 (1.74)	1.67 (3.31)	Marginal cost in ()
MR 20% ($/lb.)		1.02 (2.49)	2.62	Marginal cost in ()

RPE compared for MR. Source: Tables 5-138,139 and 5-157 to 5-164 in the 2016 TAR, Tables 6-69, 6-74 and 6-60,61 in the 2018 PRIA

Retail price effects were compared for mass reduction because EPA developed a different methodology in the 2016 TAR to compute costs for this technology. In general, for mass reduction up to 15%, the direct manufacturing cost was found to be negative (i.e., a cost saving), but EPA assumed the indirect costs were positive so that total cost was a sum of positive and negative cost which could be positive or negative. In contrast, the 2018 costs used NHTSA cost curves for computing the cost of mass reduction and there were no negative costs in the NHTSA cost curves. Hence, there is a very large differential between the costs of mass reduction, with the 2018 average cost being higher than even the 2016 marginal costs. Note that the 2016 analysis projected cost savings for mass reduction up to 10%, whereas the PRIA has large positive cost. As an example, a midsize car with a 2016 weight of 3500 lbs. undergoing a 10% (350 lbs.) weight reduction would have a cost savings of $26.25 in the 2016 analysis while this would have a cost of $297.50 in the 2018 analysis, a cost increase of about $324 from this one technology alone.

The costs for auxiliary technologies are similar between the TAR and PRIA, with the costs of EPS and Low Drag Brakes being identical at $94 and $65 respectively. Secondary axle disconnect costs are slightly different between the two reports at $84 in the 2016 TAR and $89 in the 2018 PRIA but improved accessories are considered differently. The 2016 TAR has 2 levels of improvements (IACC1 and IACC2) respectively at $77 and $124, while the 2018 PRIA employs only one level of improved accessories technology, which corresponds to the level 2 IACC in the Draft TAR analysis. The new analysis claims that the agencies have identified widespread application of the previously described IACC level 1 technologies, such as high efficiency alternators. The PRIA considers *higher* efficiency alternators for level 2 IACCs, which incorporate mild regeneration and further electrification of accessories, such as electric water pumps. For the 2018 analysis, the costs are based on the difference between IACC1 and IACC2 costs, at $50 (which appears to be inconsistent with the cost of accessory electrification which is more expensive). This implies that the effectiveness of IACC1 are completely used up in the 2016 baseline fleet for the PRIA.

3.3 Comparison of Technology Effectiveness Estimates

The estimates of technology effectiveness are more difficult than those for costs for two reasons. First, the benefit of any technology in terms of GHG reduction or fuel consumption decrease is dependent on what other technologies are present on a vehicle due to positive and negative synergies between technologies. Second, the PRIA has defined bundles of engine technologies and provided benefit estimates for only the bundles. However, the technologies within each bundle are not fully defined, notably in the area of friction reduction, lubricants and the first generation of accessory improvements. As noted, the PRIA only alludes to the fact that friction reduction is present in the maps characterizing advanced engines, but does not specifically state what level of friction reduction is included in the baseline engine (from which effectiveness are incrementally calculated). The PRIA also does not state if the baseline vehicle contains the so called IACC1 accessory technology in the simulation modeling performed.

The 2018 PRIA relied on simulation modeling with the Autonomie model developed by Argonne National Laboratory. The simulation modeling was conducted for 10 vehicle types that included all combinations of technology and the GHG effectiveness of all possible combinations for the

10 vehicle types have been provided in publicly available files The 2016 TAR does not directly provide the effectiveness of technology or technology bundles in most instances, but EPA has provided access to the Lumped Parameter Model (LPM) that allows users to select technologies for modeling and provided the technology benefit in terms of GHG reduction for any chosen set of technologies. The LPM is the model used by EPA to develop its technology effectiveness estimates utilized in the 2016 TAR

In the following tables the technologies effectiveness have been defined relative to a baseline midsize car that has 4-valve double overhead cam (DOHC) engine with VVT (dual cam phasers) and without turbocharging coupled to a 6-speed automatic transmission. This combination of engine/transmission technology was the most widely used combination in the 2016 database. This is not the combination representing the baseline for PRIA analysis or the LPM, so that the effectiveness of these technologies were subtracted out of the estimates from the LPM or the NHTSA data files. In addition, we have assumed the inclusion of lubricants and friction reduction technology in the PRIA's technology pathway based on understanding obtained from agency staff comments. The pathways are shown in Figure 3-1 (reproduced from the PRIA).

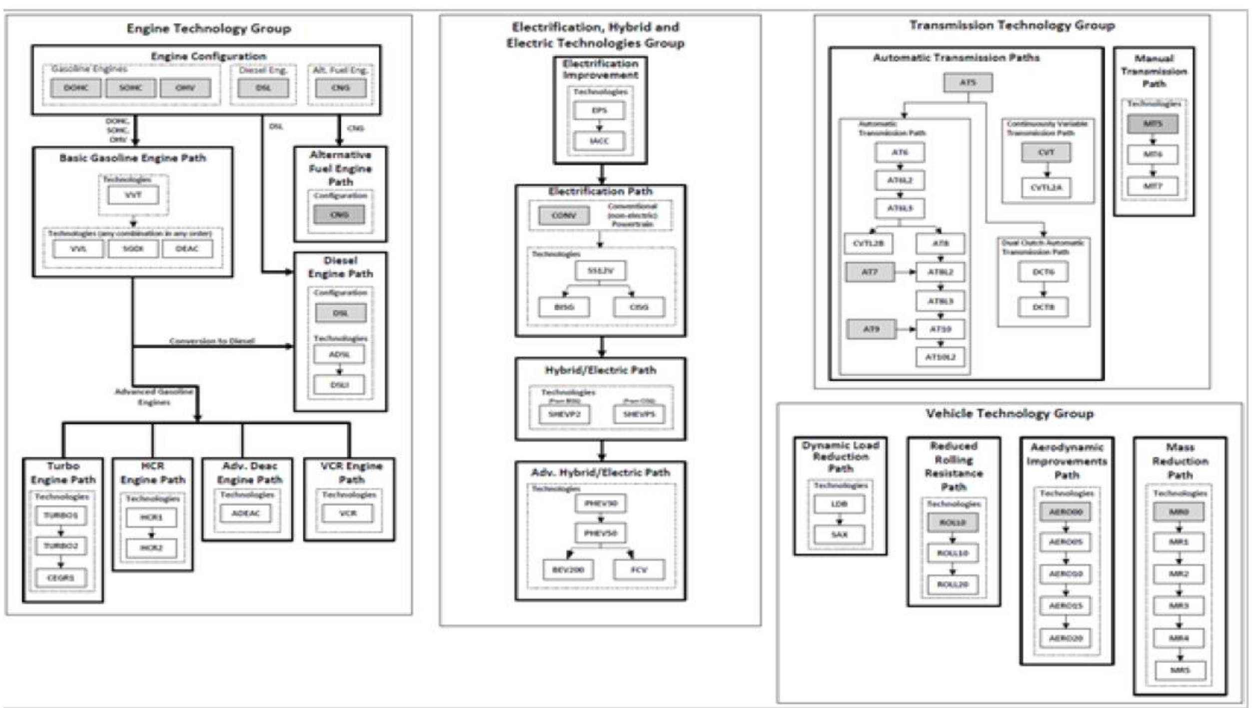

Figure 3-1: Technology Pathways used in the PRIA

Based on the pathways, we assumed that the baseline did NOT contain any friction reduction technology, and the base path (first box under configurations on the left of Figure 3-1) included lubricant technology, while all of the advanced engines included lubricants and both levels of friction reduction modeled in the 2016 TAR as this gave the closest match to benefit results from the LPM. We also assumed that IACC1 technology was used in the PRIA baseline as stated. The engine technology effectiveness estimates are shown in Table 3-6.

In general, the PRIA and TAR numbers agree within relative 5% (e,g., 10% vs 10.5%) if our technology application is correct except in the case of Turbo + cooled EGR. It should be noted that the PRIA analysis estimates zero benefit for cooled EGR relative to Turbo – 24 bar technology. The PRIA has modeled the HCR2 engine but has not included it in its analysis of compliance pathways. The PRIA states that the engine map "was developed assuming high octane Tier 3 fuel and had unresolved issues associated with knock mitigation and cylinder deactivation" used in the 2016 analysis. On the other hand, the 2018 analysis included Advanced Cylinder De-activation (ADEAC) which has recently come to market readiness.

Table 3-6: Comparison of Engine Technology Effectiveness (% GHG Reduction*)

Technology		LPM Effectiveness	PRIA Effectiveness	Technology for LPM
VVL -Continuous		3.2	3.73	LPM includes LUB
DEAC		2.5	2.49	LPM includes LUB
SGDI		2.0	1.92	LPM includes LUB
SGDI +DEAC		3.8	3.97	LPM includes LUB
TURBO – 18 bar		12.8	13.3	Includes SGDI, VVL, FRIC2, LUB and TURBO18
TURBO- 24bar		14.6	15.3	Includes SGDI, VVL, FRIC2, LUB and TURBO24
TURBO – 24 bar +CEGR		18.1	15.3	Above + CEGR
HCR1		12.5	13.4	Included SGDI, VVL, FRIC2, LUB and ATK1
HCR2		19.8	18.6	Above + ATK2 w/EGR instead of ATK1
ADEAC		NA	11.4	Not modeled in 2016

*Relative to baseline midsize car, DOHC 4V VVT PFI engine, 6AT

Table 3-7 compares the estimates of effectiveness for transmission and electrification technologies from the 2016 TAR as modeled by the LPM and the 2018 PRIA. As noted in section 3.2, the transmission technologies are not similarly defined in the TAR and PRIA, so the comparisons are inexact. The transmission friction reduction labelled as L1, L2 and L3 in the PRIA result in very different effectiveness improvements across different transmissions and no explanation for these inconsistencies are provided in the PRIA. However, the maximum benefit from transmission technology estimated in the TAR at 10.7% is significantly higher than the maximum benefit in the PRIA (for the 10ATL2 transmission) at 8.0%.

Table 3-7: Comparison Transmission and Electrification Technology Effectiveness

Technology		LPM Benefit	PRIA Benefit	Technology in PRIA
6-AT with HEG1		1.5	5.35	Technology mis-match?
6-AT with HEG2		6.1	6.00	AT6L3
8-AT		7.0	5.85	AT8
8-AT with HEG1		7.9	7.03	AT8L2
8-AT with HEG 2		10.7	7.63/8.0	AT8L3/AT10L2
Start-Stop		2.7	1.88	
Mild Hybrid BAS48V		8.2	5.35	
Strong Hybrid P2		18.4	21.92	PRIA package estimated
Strong Hybrid PS*		38.7	39.67	PRIA package estimated

*Relative to baseline midsize car, DOHC 4V VVT PFI engine, 6AT. Strong Hybrid includes low friction Atkinson cycle engine with CEGR and EPS as well as a HEG2 transmission as inputs to the LPM.

Effectiveness from stop-start and Mild Hybrid 48V systems are also significantly lower in the 2018 PRIA, relative to the effectiveness forecast in the TAR. On the other hand, the LPM estimates somewhat lower values for the mild hybrid's effectiveness in comparison to those published in 2018 although it is not clear if some of the difference is due to other technologies included in the mild hybrid package such as electric power steering or transmission friction reduction in the 2018 PRIA. There is also some lack of clarity in the assumptions for the Power Split hybrid in the PRIA, but for the LPM, we included a low friction Atkinson-2 engine with cooled EGR, an 8-speed automatic with HEG2 friction reduction as equivalent to the electric CVT, EPS and low drag brakes with the P2 option to simulate a PS hybrid which was not used in the 2016 TAR forecast. The PRIA estimates for effectiveness for the strong hybrids are generally more optimistic than those from the LPM.

The benefit estimates for body technologies and for auxiliary system technologies from the TAR and PRIA are compared in Table 3-8. The auxiliary system technology effectiveness are identical in both analyses, but the effectiveness of rolling resistance and drag reduction are significantly reduced in the PRIA. In addition, the effects of mass reduction in the PRIA are assumed to be only for the weight of the glider (vehicle without powertrain) and the weight of the glider is assumed to be only 50% of the total vehicle weight. The 50% assumption is most unusual as tear down studies (even those cited in the PRIA) show the weight of the powertrain to be only about 22 $\pm$2 % of total weight for most passenger vehicles and somewhat higher for cargo trucks. Hence in the PRIA, a 5% weight reduction is equal to a 2.5% weight reduction of the vehicle, while weight reductions of 10% and above account for some powertrain weight reduction so that a 10% weight reduction is equivalent to about 6.5% net vehicle weight reduction.

Table 3-8: Body Technology Effectiveness, % Reduction in Fuel Consumption

Technology		LPM Benefit	PRIA Benefit	Technology in PRIA
Rolling Resistance -10%		2.2	1.54	
Rolling Resistance -20%		4.4	3.06	
Aero Drag -10%		2.1	1.51	
Aero Drag -20%		4.3	3.03	
Mass Reduction 5%		2.6	0.88	Different assumption in PRIA regarding vehicle weight reduction.
Mass Reduction 10%		5.2	3.33	
Mass Reduction 15%		7.7	5.31	
Mass Reduction 20%		10.4	6.92	
Electric Power Steering		1.3	1.3	
Improved Accessories1		1.2	1.22	
Improved Accessories2		2.3	2.36	
Low Drag Brakes		0.8	0.8	
Secondary Axle Disconnect		1.4	1.4	

*Relative to baseline midsize car, DOHC 4V VVT PFI engine, 6AT

3.4 Findings

A detailed analysis of technology costs in the 2016 TAR and 2018 PRIA showed that costs for most conventional (i.e., non-electric) drivetrain technologies were similar in both reports in that costs were within ±5% of the average of the costs from the two reports. The only exception was the cost estimate for the High CR second generation Atkinson cycle or HCR2 engine which was estimated to be much more expensive. Due to differences in nomenclature, transmission technology costs could not be directly compared but were similar at the highest efficiency level. In contrast, cost of hybrid technology was estimated to be much higher in the PRIA and were 200 to 250% higher for strong hybrids. Costs of drag reduction, rolling resistance reduction and auxiliary system technologies were also quite similar but the cost of mass reduction was substantially higher in the PRIA by a factor to 2 to 3. Costs of engine friction reduction appear not to be included in the cost computation for the PRIA although the technology appears to be integrated into some of the engine technology packages analyzed in the PRIA to estimate effectiveness.

Benefit estimates for all engine technologies except for Turbo-charging + Cooled EGR were comparable, given our assumptions about the use of engine friction technology in the PRIA.

However, the effectiveness of transmission technology are lower in the PRIA for all levels of transmissions, as are the effectiveness for stop-start and mild hybrids. In contrast effectiveness for strong hybrids of the P2 and PS types are higher but this could be due to potential differences in the technology packages that underlie these technology names.

Effectiveness for all body technologies are also lower in the PRIA, with mass reduction effectiveness being significantly lower due to assumptions in the PRIA about how it is implemented.

The increases in net costs to attain augural standards in 2025 in the PRIA relative to those in the TAR are therefore related to the following issues:

- Several low-cost conventional technologies have significantly lower effectiveness in the 2018 PRIA.
- This is a significant, but not the only driver for the need to use more mild and strong hybrids in the 2018 PRIA so that their market penetration required to meet the standard in higher than estimated in the 2016 TAR
- In addition, the costs of mild and strong hybrids have been increased by 200 to 250 percent in CY2016, making the cost of attaining the 2025 standard much higher
- The changes do not affect cost of compliance with 2020 standards, which can be met without the use of hybrids even with the lower effectiveness assumed for several low-cost conventional technologies.
- In addition, the cost of engine friction reduction does not appear to be included in the 2018 PRIA results possibly due to inadvertent omission.

4 CRITIQUE OF THE METHODOLOGY AND DATA USED IN THE PRIA

4.1 Overview of the NHTSA Forecasting Methodology

The detailed analysis of the compliance pathways, technologies and costs in Sections 2 and 3 of this report identified specific technologies for which the costs and/or effectiveness used in the PRIA are significantly different from those used in the 2012 and 2016 analysis. The technology costs and effectiveness are inputs to the CAFE model which utilizes this information to project compliance with CAFE standards at the vehicle model level and manufacturer level. A brief summary of the methodology used in the model is provided below.

The costs and effectiveness of technology improvements have been developed externally to the CAFE model. Most of the **cost** numbers are identical or are based on small adjustments to the cost numbers developed in 2012 and updated in 2016. However, some technologies' costs have been revised significantly but there is little or no documentation on how the new cost numbers were estimated. Technology cost data that have been significantly revised in the 2018 PRIA are critiqued in Section 4.3.

The **effectiveness** of technologies and technology combinations have been developed by Argonne National Laboratory using the "Autonomie" simulation model. The simulation model itself requires inputs on engine and transmission maps as well their implementation in a vehicle. While many of the effectiveness estimates are similar to those employed in the 2012 and 2016 analyses, estimates for some technologies are significantly different and the derivation of these effectiveness estimates is critiqued in Section 4.4.

The PRIA analysis uses the CAFE model to estimate how manufacturers could comply with a given CAFE standard by adding technology to fleets that the manufacturers could produce in future model years. It simulates manufacturers' decisions regarding compliance with CAFE or GHG standards. This compliance simulation begins with the following inputs - (a) the baseline fleet of vehicles from model year 2016, (b) fuel economy improving technology estimates, (c) economic inputs, and (d) inputs defining baseline and potential new CAFE standards. For each manufacturer, the model applies technologies in what NHTSA terms is a "logical" sequence and uses a cost-minimizing strategy in order to identify a set of technologies the manufacturer could adopt in response to CAFE or GHG standards. The model applies technologies to each of the projected individual vehicles in a manufacturer's fleet, considering the combined effect of regulatory and market incentives while attempting to account for manufacturers' production constraints. Depending on how the model is exercised, it will apply technology until one of the following occurs:

(1) The manufacturer's fleet achieves compliance with the applicable standard, but can continue to add technology in the current model year if it can facilitate compliance in future model years (using carry forward credits);

(2) The manufacturer uses up all "available" technology; or

(3) For manufacturers assumed to be willing to pay civil penalties, the manufacturer reaches the point at which paying penalties would be more cost-effective than adding further technology to meet CAFE standards. (Some manufacturers are simulated as being unwilling to pay CAFE penalties). It should be noted that the GHG program does not allow non-compliance so the civil penalty issue is unique to CAFE compliance.

A key issue here is the definition of "available" as the model constrains adoption of many technologies to years when a vehicle is expected to be redesigned, and also constrains the adoption of specific engine technologies by specific manufacturers depending on what these manufacturers had adopted in the base year, 2016. The model accounts explicitly for each model year, applying "available" technologies when vehicles are scheduled to be redesigned or refreshed, and carrying forward technologies between model years once they are applied until (if applicable) they are superseded by other technologies. The CAFE model accounts explicitly for each model year, because manufacturers actually carry forward most technologies between model years, and NHTSA asserts that manufacturers concentrate the application of new technology to vehicle redesign or mid-cycle freshening years. NHTSA uses design cycles that could vary widely between manufacturers and specific products. Year-by-year accounting also enables accounting for credit banking.

As in previous CAFE rulemaking analysis, the simulation of technology adoption is constrained by the pace at which new technologies can be applied in the new vehicle market. In the model, redesign and refresh cycles are specified at the make/model level and as noted, most technologies can be applied to that specific make/model only in those years. For every vehicle model that appears in the MY 2016 analysis fleet, NHTSA estimated the model years in which future redesigns and freshening will occur. However, it should be noted that the PRIA analysis does not account for future new products or discontinued products. These characterizations of product cadence are important to any evaluation of the impacts of CAFE or GHG standards, but NHTSA agrees they are not known with certainty – even by the manufacturers themselves over time horizons to 2025/ 2030. Hence, NHTSA researchers' subjective opinions on product cadence also govern CAFE compliance, and this factor makes the compliance estimates subject to arbitrary decisions.

In the current CAFE model, engines and transmissions that are shared between vehicles must apply the same levels of technology, in all technologies, dictated by engine or transmission inheritance. The CAFE model first chooses an “engine leader” among vehicles sharing the same engine – the vehicle with the highest sales in MY 2016**.** If there is a tie, the vehicle with the highest average MSRP is chosen, representing the idea that manufacturers will choose to pilot the newest technology on premium vehicles if possible. The model applies the same logic with respect to the application of transmission changes. After the model modifies the engine on the “engine leader” (or “transmission leader”), the changes to that engine propagate through to the other vehicles that share that engine or transmission in subsequent years as those vehicles are redesigned.

The CAFE model defines technology pathways for grouping and establishing a “logical” progression of technologies on a vehicle. Each pathway (or path) is evaluated in the model independently and in parallel, with technologies on these paths being considered in sequential order specified. As the model traverses each path, the costs and fuel economy improvements are accumulated on an incremental basis with relation to the preceding technology. The system stops examining a given path once a combination of one or more technologies results in a “best” technology solution for that path. After evaluating all paths, the model selects the most cost-effective solution among all pathways. The documentation states that the parallel path approach allows the model to progress thorough technologies in any given pathway “without being unnecessarily prevented from considering technologies in other paths”. While this version of the CAFE model allows basic engine technologies to be applied in any order once an engine has VVT (the base state of all ANL simulations) it actually does **not** allow unconstrained choice. Once the model progresses past the basic engine path, it considers all of the more advanced engine paths (Turbo, HCR, Diesel, and ADEAC) simultaneously. They are assumed to be mutually exclusive, and once one path is taken, it locks out the others.

4.2 Critique of Modeling Methodology

The methodology used in the CAFÉ model used to develop the estimates has three significant issues based on our evaluation

- Assumptions regarding the baseline
- Specification of product cadence
- Constraints on technology adoption

Each of these issues is considered in more detail below.

4.2.1 Baseline

A key assumption in the model is that vehicle fuel economy baseline year 2016 is fully characterized by the certification fuel economy level and the specific technology associated with a particular make/model. For example, a 2016 Ford Fusion with a 1.5L direct injection turbo engine rated at 36.26 mpg would be represented in the model as having VVT, GDI, Turbo-18bar, stop-start, etc. Since the future fuel economy increases are based on adding technologies not in the baseline and the computation of fuel economy based on percent increases associated with added technology starting from the 36.26 mpg level, any other factor distorting the baseline fuel economy is carried forward over the forecast period. An assessment of the actual certification fuel economy levels for different make/model vehicles show that there are large fuel variations in fuel economy between near identical models from different manufacturers even though the technological differences between models may be minimal or explain very little of the difference observed. The 2016 midsize car class is used as an example to demonstrate how this distorts the forecast and cost computation.

Table 4-1: 2016 Actual Baseline for Popular Mid-size Cars

Vehicle		Engine	Fuel Sys.	Turbo	Trans.	FE mpg	% FC difference
Ford Fusion		1.5L	DI	Yes	A6	38.91	-11.8
Chevy Malibu		1.5L	DI	Yes	A6	41.10	-6.80
Honda Accord		2.4L VVL	DI	No	CVT	41.30	-6.35
Hyundai Sonata		1.6L	DI	Yes	A7	42.41	-3.8
Nissan Altima		2.5L	PFI	No	CVT	44.10	Ref.
Toyota Camry		2.5L	PFI	No	A6	36.90	-16.3

Source: EPA 2016 Fuel Economy Guide Data

Table 4-1 shows several midsize cars that have very similar size, weight and power ratings, and the most efficient is the Nissan Altima which has a naturally aspirated 2.5L engine with PFI and VVT; in fact, the only drivetrain technology that lifts it above the CAFÉ model's "null" technology vehicle is the CVT. In contrast, the Fusion utilizes a 1.5L DI-Turbo engine with stop-start and nearly identical horsepower as the Altima but its fuel economy is about 12% less than that of the Altima. The Toyota Camry employs the same observable technology as the Altima except for tor the CVT, but this difference cannot explain the 16.3% difference in fuel consumption. The baseline distortion persists over the entire forecast period and causes significant differentials in the technologies needed for compliance with augural 2025 standards.

The PRIA forecast comparison between the Chevy Malibu and Honda Accord is very instructive as they start in 2016 with similar weight, power and nearly identical fuel economy levels. The CAFE model classifies the starting 2016 technology as follows

Accord – VVL, GDI, CVT, CONV, MR0, AERO0, ROLL20

Malibu – TURBO1, AT6, SS12V, MR5, AERO0, ROLL10

Note that the Malibu has much higher baseline technology penetration including the downsized Turbo package that includes GDI and VVL, 5% mass reduction and stop-start, while the Accord has only the CVT and an extra 10% reduction in rolling resistance. The estimated improvement for the Accord's 2016 technologies over a null technology vehicle is 15.7% while the improvement for the Malibu is 24.1%. Hence the null technology Accord would be rated at 35.7 mpg while the null technology Malibu would be rated 33.1 mpg giving the Accord a 7.1% fuel consumption advantage at the same technology level. Since the technology adoption benefit is estimated by a percentage multiplication of the base fuel economy, the null technology 7.1% advantage grows in mpg space with technology adoption. This is an obvious issue for the model and methodology since technologically identical vehicles from different manufacturers would be forecast to have significantly different fuel economy.

The forecast is also instructive as the path for the Accord includes MR1, advanced CVT2 and the Turbo1 package by 2022 to reach a forecast fuel economy level of 49.16 mpg. Interestingly, the actual redesigned 2018 Accord has essentially adopted the same technologies as those in the 2022 forecast, offering a 1.5L Turbo (same displacement as the Malibu's engine) and weight reduction equivalent to the MR1 level, but the 2018 actual fuel economy is only 42.83 mpg, a 14.8% difference from the forecast level. As a result of these differentials, the Accord is estimated to attain 57.1 mpg at a cost of $538 by 2025, while the Malibu attains only 51.47 mpg at a cost $1567 in 2025. The very high cost differential of over $1000 between the Malibu and Accord is largely due to the forecast that the Malibu needs a mild hybrid system to comply with 2025 standards while the Accord does not (as noted, the mild hybrid system cost is much higher than estimated in previous analysis). Note that the mild hybrid reduces fuel consumption by less than 6% in the PRIA forecast, so that the baseline differential at identical null technology between the Accord and Malibu is larger than the mild hybrid improvement for the Malibu.

The issues with the baseline are often (but not always) associated with less than optimal technology integration in early years of technology introduction followed by growth in fuel economy as the system is optimized. The Malibu's 1.5L turbo was a new entrant for 2016 and it is possible that the Malibu's fuel economy can increase with calibration maturity for the same system at zero cost. Another possibility is that Japanese manufacturers can obtain higher fuel economy levels with the same technology than GM, Ford and FCA, as their advantage at similar technology levels appear to persist over time. The resolution of this issue is required to make the forecast costs similar for similar vehicles.

4.2.2. Product Cadence

The model assumes that most technological changes can be made only during vehicle redesign or for some technologies, during a product freshening. Hence, the cadence of product introduction controls the rate of technology introduction and can cause over-compliance in some years prior to 2025 if the next redesign or freshening is specified to be beyond 2025. We agree that product cadence can affect technology introduction rates but the tailoring of the CAFÉ model's product cadence to actual product cadence is problematic. NHTSA has an inconsistent position on this issue as many statements in the PRIA suggest that one goal was to make the model as "realistic" as possible while a second goal was to estimate what manufacturers were capable of achieving.

In order to develop the redesign schedules, the PRIA describes the process as follows from page 524 of the PRIA : "Based on historical observations and refresh/redesign schedule forecasts, careful consideration is given to redesign cycles for each manufacturer, and each vehicle is important. Simply assuming every vehicle is redesigned in 2021 and 2025 is not appropriate, as this would misrepresent both the likely timing of redesigns and the likely timing between redesigns in nearly all cases. To develop the refresh/redesign cycles used in the fleet, this analysis used information from Ward's Automotive and other sources to project redesign cycles through 2022. For years 2023- 2035, Volpe Center staff extended redesign schedules based on Ward's *projections, segment, and platform history, and anticipated competitive pressures*."

However, when model's reviewers complained that the forecasts did not match what was actually happening in 2017/18, the response from NHTSA was as follows[3]: "Because the model is intended to estimate ways manufacturers *could* (not *should* or *will*) respond to standards, we do not expect the model to reproduce manufacturers' *actual* decisions, especially when inputs are not informed by confidential detailed product planning information".

The conflict here is between what manufacturers "could" accomplish versus what their "actual decisions" are. If the process of developing the redesign cycles used industry information, it is difficult to see this data as representing what the manufacturers "could" accomplish rather than as an attempt to model their actual plan. The moral hazard that arises with using actual decisions is when a hypothetical manufacturer decides to cut capital spending and redesign its vehicles every 10 years instead of every five to spend more on lobbying to repeal CAFE standards. NHTSA would then use this information on product plans in the CAFE model to suggest it is impossible for the hypothetical manufacturer to meet the standard, thereby rewarding their effort to undermine standards.

[3] NHTSA "CAFE Model Peer Review" Page 12, Report No. DOT HS 812 590, July 2018

Table 4-2: Sales Weighted Average Time Between Redesigns (years)

Manufacturer	SmallCar	SmallCarPerf	MedCar	MedCarPerf	SmallSUV	SmallSUVPerf	MedSUV	MedSUVPerf	Pickup	PickupHT	ALL CLASSES
BMW	6.0	6.1	6.7	6.5	5.5	6.4	6.3	6.1	-	-	6.3
Daimler	7.0	5.5	7.0	6.6	5.6	7.0	10.0	7.3	-	-	6.7
FCA	6.2	6.1	6.0	8.2	9.0	7.4	8.3	8.7	10.0	10.0	8.6
Ford	8.3	8.5	6.3	6.9	7.7	7.6	7.4	7.9	5.8	5.8	7.1
General Motors	5.7	5.2	5.0	6.2	5.7	7.3	7.4	6.1	6.5	7.9	6.3
Honda	4.4	4.8	4.8	4.9	5.5	5.8	-	6.0	-	-	5.3
Hyundai Kia-H	5.0	4.8	5.3	6.0	5.3	5.3	5.3	5.3	-	-	5.2
Hyundai Kia-K	5.7	6.0	5.5	5.0	4.7	5.5	5.5	7.1	-	-	5.4
JLR	-	-	-	7.5	-	6.3	-	6.4	-	-	6.5
Mazda	-	6.4	4.2	7.7	5.1	7.0	-	7.0	-	-	5.4
Nissan Mitsubishi	5.1	5.7	5.5	6.0	6.9	6.6	-	6.5	8.0	-	6.1
SUBARU	4.8	7.8	5.4	4.7	5.4	5.5	-	-	-	-	5.4
Tesla	-	-	-	10.0	-	-	-	10.0	-	-	10.0
TOYOTA	5.5	9.6	6.3	6.0	5.3	5.7	5.3	7.2	10.5	10.1	6.6
Volvo	-	8.3	-	8.6	-	8.0	-	7.2	-	-	7.8
VWA	-	5.9	7.3	6.0	7.7	7.1	-	7.6	-	-	6.6
TOTAL	5.5	6.0	5.6	6.7	6.2	6.6	7.2	7.1	8.1	7.8	6.5

The actual data used in the analysis to develop estimates of product cadence also illustrates the problem. As can be seen from Table 4-2 (reproduced from Table 6-99 of the PRIA), the years between redesign vary a lot between manufacturers and even across products offered by the same manufacturer. (It is unclear how values for Tesla were obtained as Model S and X are only 6 and 3 years old) There is no technical reason why Ford should redesign its small cars every 8.5 years when GM redesigns its small cars every 5.2 years or Toyota does so every 5.5 years. Looking across Toyota's product line suggests that some vehicles are on 10+ year cycles and others on 5-year cycles. The reason for these differences has more to do with the financial health of the manufacturer and the competition in the class, but it is not clear how NHTSA projects what the profitability of any specific manufacturer will be or how competitive its product will be in the future to develop the redesign schedule at the model level, and the cadence is just a subjective estimate by Volpe staff. We agree that the redesign/ refresh schedule is important for **some** technologies and suggest that the only relevant information from Table 4-2 is that the average redesign cycle is about 5 to 6 years. Note that Ford's redesign cycle for the pickup is listed as 5.8 years even though the PRIA especially cites pickups as having the longest redesign cycle, while Ford has the highest market share in this class. To avoid the moral hazard issue and make the analysis a projection of what manufacturers **could** do, we advocate a standard redesign cycle of 5 to 6 years for all products with a refresh at 3 years.

4.2.3 Constraints on Technology Introduction

There are several constraints on technology penetration in the model which bias costs of compliance upwards and the include the technology pathway specified, the link between technology adoption and product cadence, and the sharing and "inheritance" requirements among platforms and shared engines and transmissions.

The **technology pathway** forces the introduction of at least one cost ineffective technology and prevents consideration of several cost-effective combinations of technology. Cost-effectiveness is defined here as the cost per percent decrease in fuel consumption or CO2 emissions. Based on data presented in the 2016 TAR, most conventional technologies (i.e. without electrification) cost $60 or less per percent reduction of GHG emissions while most electrified technology costs $120 or more per percent. In this context, the prescribed pathway in the 2018 PRIA always includes continuously variable valve lift (VVL) which is cost ineffective compared to other conventional technologies even with the base gasoline engine, providing a 3.73% fuel consumption reduction in a midsize car at $314, or about $85 per percent reduction. The Lumped Parameter Model (LPM) suggests a smaller benefit at 2.6% which would decrease the cost effectiveness to $120 per percent. The effectiveness of VVL is even smaller when this technology is combined with turbocharging and downsizing (the preferred pathway for a majority of vehicles) with its marginal effectiveness decreasing to 1.5%, and further to 1.4% when an 8-speed transmission is added (according to the LPM). This reduces cost effectiveness to $224 per percent, making VVL more expensive per percent reduction than several electrification technologies. Thus, removing the VVL from the base pathway would save $314 but reduce fuel economy by only 1.4%.

By forcing the model to choose between advanced technologies (TURBO, ADEAC, HCR) as <u>mutually exclusive</u> paths, combinations of these technologies that are very cost-effective are excluded from consideration. This includes the combination of turbocharging and higher compression ratio (TURBO+HCR) that EPA studied extensively as the Miller cycle in the 2016 TAR. This type of engine is listed in the PRIA as one of the options that could be investigated for future analysis and is listed as "IAV engine 24". It is unclear why this engine was not included in the 2018 analysis since VW has introduced this type of engine into the market in MY2017. The EPA analysis in the TAR indicates that the additional benefit to fuel consumption and CO2 is about 5% relative to 24-bar turbo technology while costs to implement the Miller cycle incremental to the 24-bar turbo were judged to be near zero making it infinitely cost effective. Ford appears to be implementing a similar strategy in the 2.7L and 3.5L V6 engines as the CR of these turbocharged engines has increased recently without requiring the use of premium gasoline. Similarly, there is no technical reason impeding the combination of ADEAC technology with either HCR engines or TURBO engines and GM has announced the introduction of a turbocharged engine with ADEAC for MY2020.

Table 4-3: Body Redesign and Technology Introduction Dates for Three Popular Vehicles

Year	Chevy Malibu	Ford F-150	Jeep Grand Cherokee
2009		Body Redesign 6-spd. automatic	
2010			
2011	6-speed automatic	New 3.5 turbo, 3.7L V6 and 5.0L V8	Body redesign New 3.6L V6
2012		Body refresh 6.2L V8 added	New 6.4L V8
2013	Body Redesign 3.5l V6 dropped		
2014	Mid-year refresh New 6-spd automatic		Minor body refresh 3L Diesel V6 8-spd 845RE automatic
2015	Stop Start on 2.5L	Body redesign 2.7L turbo V6	
2016	Body Redesign New 1.5 and 2.0L Turbo engines		
2017		10-spd. Automatic with 450 HP 3.5L V6	Minor refresh
2018	9-speed automatic	Body refresh New 3.3L V6 10-spd. Automatic with all engines	New 6.2L V8 New 8-spd 850RE automatic
2019	Body Refresh New CVT	New 3L diesel	
2020		New Hybrid	Body redesign

Source: Wikipedia, manufacturer press releases.

As noted, the CAFE model **constrains most technology introduction to the redesign year** or, in some cases, the "refresh" year. All engine and all hybrid technology is restricted for adoption during a redesign, while transmission adoption can occur in redesign or refresh years. Only the MR1 and MR2 levels of weight reduction, AERO5 and ROLL10 and ROLL20 can occur in refresh years, with all other body technology becoming available only during redesigns. The actual data on technology introduction does not support these restrictions except in the case of weight reduction and higher levels of aero drag reduction. Actual technology introduction dates are not uniformly linked to the refresh/redesign cycle. Table 4-3 shows the body refresh and redesign dates as well as new engine, transmission and hybrid technology introduction over a 12- year period for three popular vehicles in different market segments. It can be seen that new engines, new transmissions, and new hybrids have been introduced in years not linked to any redesign or even a "minor" refresh (when only trim, lights and grille are changed). Accordingly, the model should be revised to allow technology introduction as required for compliance.

The final issue involves the **technology sharing and inheritance** rules. The PRIA states (pg.478) that "In previous analyses that used the CAFE model (with the exception of the Draft TAR), engines and transmissions in individual vehicle models were allowed relative freedom in technology application, potentially leading to solutions that would, if followed, create many more unique engines and transmissions than exist in the analysis fleet (or in the market) for a given model year. This multiplicity likely failed to sufficiently account for costs associated with such increased complexity in the product portfolio, and may have represented an unrealistic diffusion of products for manufacturers that are consolidating global production to increasingly smaller numbers of shared engines and platforms."

The rules involving technology leader and follower models may have been true in an era when GM had 8 divisions and Chrysler had 4 divisions, etc., and when the same vehicle type was shared across multiple divisions with different market positions, but the situation is quite different in this decade. Within GM, Cadillac has its own products for the most part with little sharing, while Buick has only a few products with 2 of 6 models in its lineup being imported, Chrysler and Dodge appear on the verge of being shut down and Lincoln models have such limited sales in comparison to Ford models that product sharing and inheritance is largely a non-issue. The PRIA provides no data from the recent past showing that the rules represent what has actually happened in the marketplace.

It is also unclear how DOT interprets these rules for Asian manufacturers – for example, Toyota produces dozens of models for global markets that share many engines, transmissions and platforms used in the USA and it is not clear how any inheritance rules can be designed without a global forecast of technology adoption (which we assume is not being done by NHTSA). Another factor is the ability of Tier I suppliers to provide complete subassemblies like transmissions, engines, hybrid systems. For example, GM buys an 8-speed transmission from Aisin, while FCA uses the ZF 8 and 9-speed automatic on most of its models, and uses Fiat sourced engines and VVL systems in North America. Outsourcing engines, transmissions and hybrid systems is one way around capital expenditure constraints that the PRIA suggests as a reason for these rules, and it also appears that such rules are implemented only for GM, Ford and FCA in the CAFE model

While removing the constraint requiring alignments of technology adoption with redesign/ refresh actions may remove much of the effect of these inheritance rules, we also suggest removing them entirely since they appear to be 1) selectively applied to some manufacturers, 2) neglect the fact that many major sub-assemblies are being outsourced to Tier 1 suppliers and 3) are not backed up by data from the last decade on the actual spread of technologies.

4.3 Critique of Technology Cost Estimates

The documentation in Section 3 identified several technologies where the cost utilized in the PRIA was significantly different from the cost used in the 2016 TAR and 2012 TSD. Significant cost changes were identified for the High Compression Ratio Atkinson cycle 2 (HCR2 or ATK2) engine, all types of hybrids, and for material substitution.

The cost data developed for the ATK2 engine by EPA was based on an extensive effort using the Mazda ATK1 engine modified by EPA, and started with 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. EPA subsequently developed hardware to permit the ATK1 engine to operate at ATK2 level of compression ratio with cooled EGR. The hardware development, engine dynamometer testing, model validation and updating of the GT-POWER model represent significant further study and development of these technologies. In the Draft 2016 TAR states that EPA "has completed much of this work, which as explained earlier, confirms that our estimates for the Proposed Determination are appropriate", showing a higher level of confidence in the $110 cost estimate.

The PRIA estimate of $317 is undocumented but sources at ARB have suggested NHTSA based this cost on the bulky exhaust system used in the Mazda ATK1 engine, which apart from being expensive also requires the vehicle to be modified to accommodate the exhaust system. In 2018, Toyota introduced the ATK2 engine into the US market in the Camry. The 2018 Camry is the most efficient non-hybrid midsize car sold in the US, and is rated at 46.84 mpg, which is 27% higher then the 2016 model shown in Table 4-1 obtained from a Toyota press release. The 2018 Camry does not have the bulky exhaust of the Mazda and press releases on the engine by Toyota show the changes made as described in Figure 4-1. None of the engine changes, with the exception of the direct injection system and cooled EGR, are expensive, and these two components have been costed in detail by

EPA. Other technologies such as the motor driven water pump and variable oil pump contribute to Camry's high efficiency but are not specifically required for the ATK2 engine. However, ATK2 technology has no effect on the PRIA cost estimates as it was not used for the forecast.

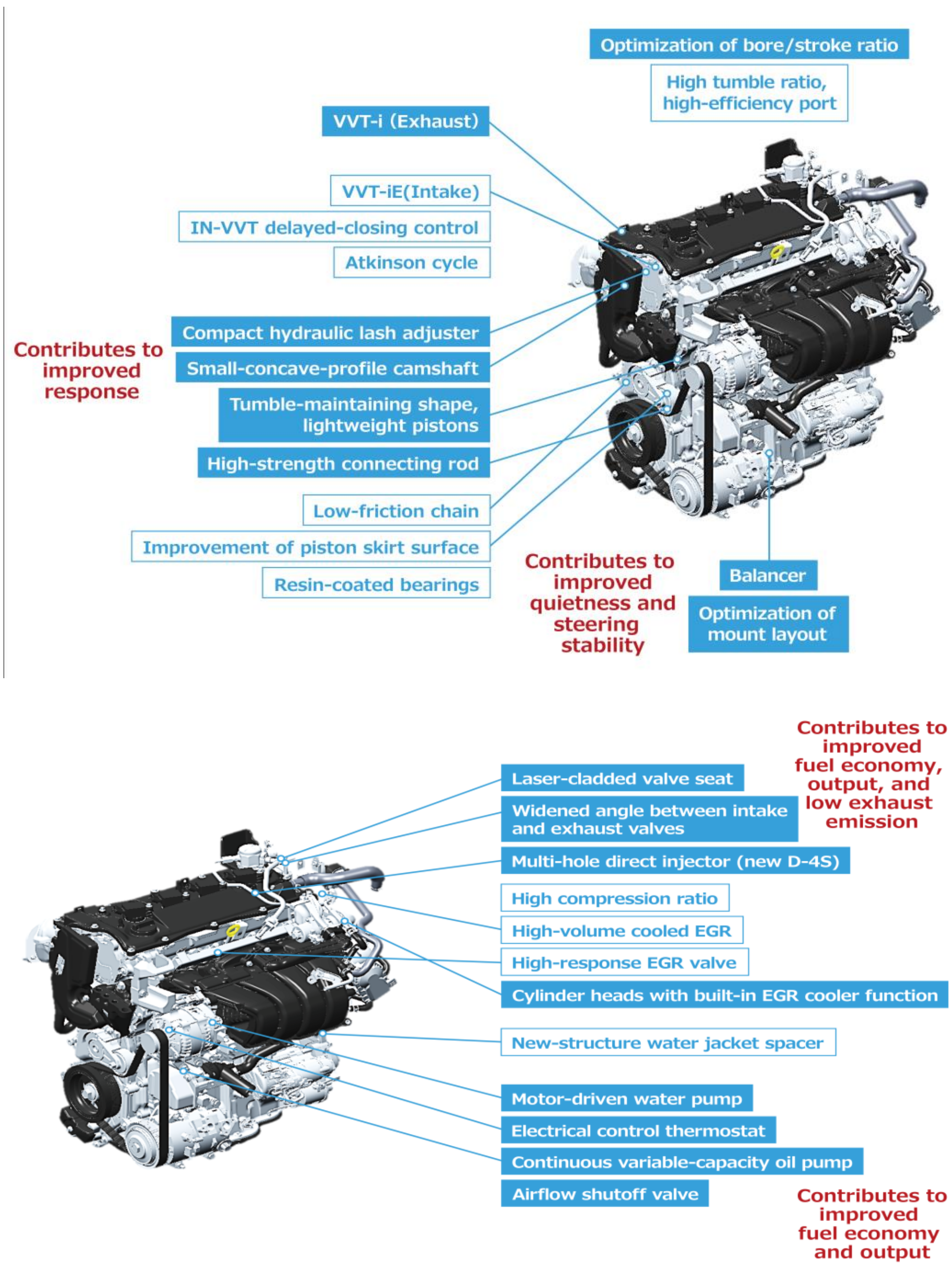

Figure 4-1: Key Technologies on Toyota's ATK2 Engine

As noted in Section 3, the costs of hybrids estimated in the 2018 PRIA are 2 to 2.5 times the costs estimated in the Draft TAR. Again, NHTSA provides no documentation of the new cost numbers, and the battery costs while higher than those in the TAR explain only a small part of the cost increase. For example, the TAR estimated a battery pack cost for the 48V BAS mild hybrid at $314 in 2017, while the PRIA cost estimate is $391, a difference of $75. However, the entire system cost is about $700 to $750 more expensive in the PRIA compared to the TAR estimate. The estimates of cost for all hybrid systems in the PRIA are surprisingly high as all of these systems have been introduced in the marketplace over 10 years ago and manufacturers and suppliers have indicated the cost of such systems in public presentations. It is possible that the system costs were extrapolated from an early GM Saturn system which was significantly overdesigned and estimated to cost $1650 by an EPA sponsored study conducted by FEV[4]

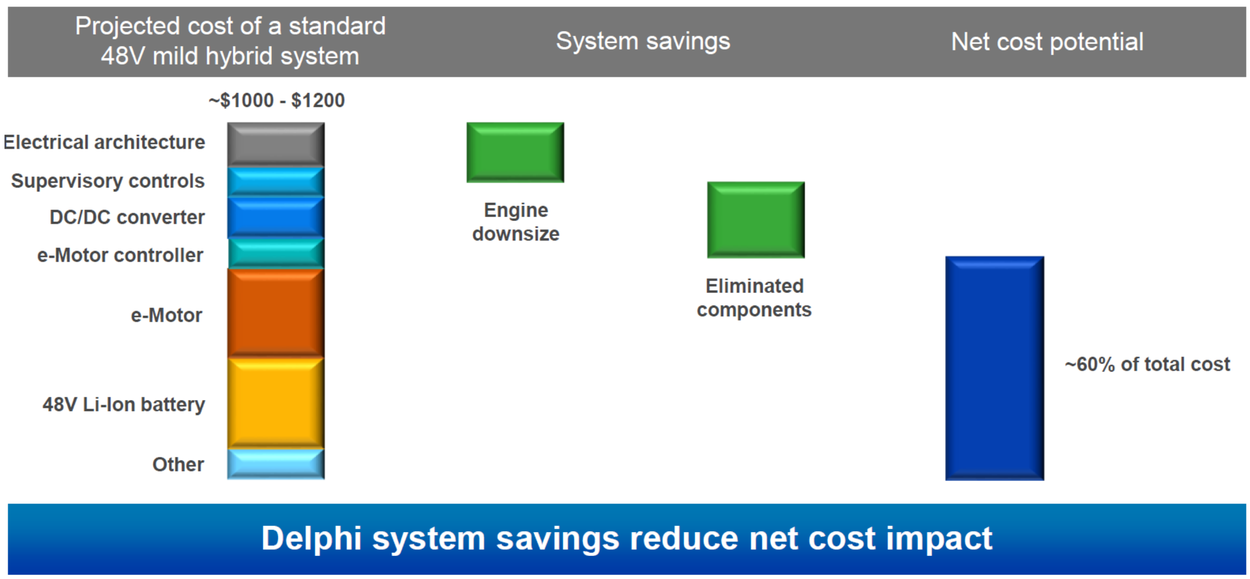

Figure 4-2: Delphi Estimates of 48V Systems Cost

The costs of the modern 48V system has been publicly discussed by Delphi[5], a supplier of such systems, and their estimates of the total cost before savings is in the $1000 to $1200 range (depending on vehicle size) as shown in Figure 4-2 above. However, the system affords the elimination of the 12V starter, alternator and battery and reduced costs for the electric power steering for a saving of about $200, and Delphi also claims some savings from engine downsizing potential. Even if the engine cost reduction is ignored, the net cost will be $800 to $1000, which is much closer to the TAR estimate than to the PRIA estimate. The 2016 battery cost estimate is potentially too high with recent rapid decreases in lithium-ion battery costs, as discussed in more detail below. A separate factor driving vehicles towards 48V solutions is autonomous driving technology which requires 1.5 to 2 kW of power in the vehicle. It is difficult

[4] FEV "Light-Duty Vehicle Technology Cost Analysis-Mild Hybrid and Valvetrain technology", EPA report EPA-420-R-11-023, October 2011
[5] Mary Gustanski "48V Investor Update" June 29, 2016 available at www.delphi.com

for a 12V system to supply so much additional power and the 48V system may be required in the future (most of today's autonomous vehicles are hybrids capable of supplying the high electric power demand).

Costs of P2 and PS hybrids have received considerable attention since the Prius was introduced and FEV did a detailed teardown analysis of the costs for clients in the EU[6]. The results of these studies are shown below:

Table 4-4: Teardown Cost Data for PS and P2 Hybrids in Compact Cars

	Input power-split	P2 hybrid
Power transmission/clutch system	$608	$300
Integrated electric motor/generator/ sensors/controls	$1,518	$675
Li-ion Battery Subsystem (1.0 kWh)	$1,375	$1,375
Electricity power distribution, inverters/converters	$379	$379
Brake, body, climate control systems	$461	$461
Credits – transmission, engine, service battery, alternator	-$1,217	-$276
TOTAL	**$3,122**	**$2,912**
Costs adjusted from 1.4:1 to 1.15:1 Dollar/Euro	**$2,565**	**$2,392**

Source: Ref. 6 footnoted below

The costs were developed in Euro which was trading at ~$1.40 in 2013 but is now around $1.15 so that a direct conversion with the new rate is shown above. This may not be completely appropriate as some components may have been imported into Europe at lower cost due to the strong Euro in 2012/13 and costs could be between the two estimates. Note that these costs, even at $3122/ $2912 levels are quite similar to EPA estimates of $2650 to $3300 (depending

[6] FEV, Light-Duty Vehicle Technology Cost Analysis – European Vehicle Market (Phase 1), (2012, updated 2013), available at https://www.theicct.org/.

on vehicle size) published in the TAR for the P2 hybrid, and also shows that the PS hybrid is just 7% more expensive than the P2 hybrid. Moreover, it is certain that battery prices have decreased significantly[7] from 2012 when the costs were estimated to be $1375 to less than $1000 so that current costs are estimated to be ~ $400 less than the $3112 and $2912 numbers shown above. As noted, the PRIA costs for these technologies are 2 to 2.5 times the above numbers, and no documentation is provided for the increased costs.

An independent method to estimate costs is from the retail price increments in the market for hybrids. An analysis by Vincentric of retail prices[8] in 2014 showed the following price increments:

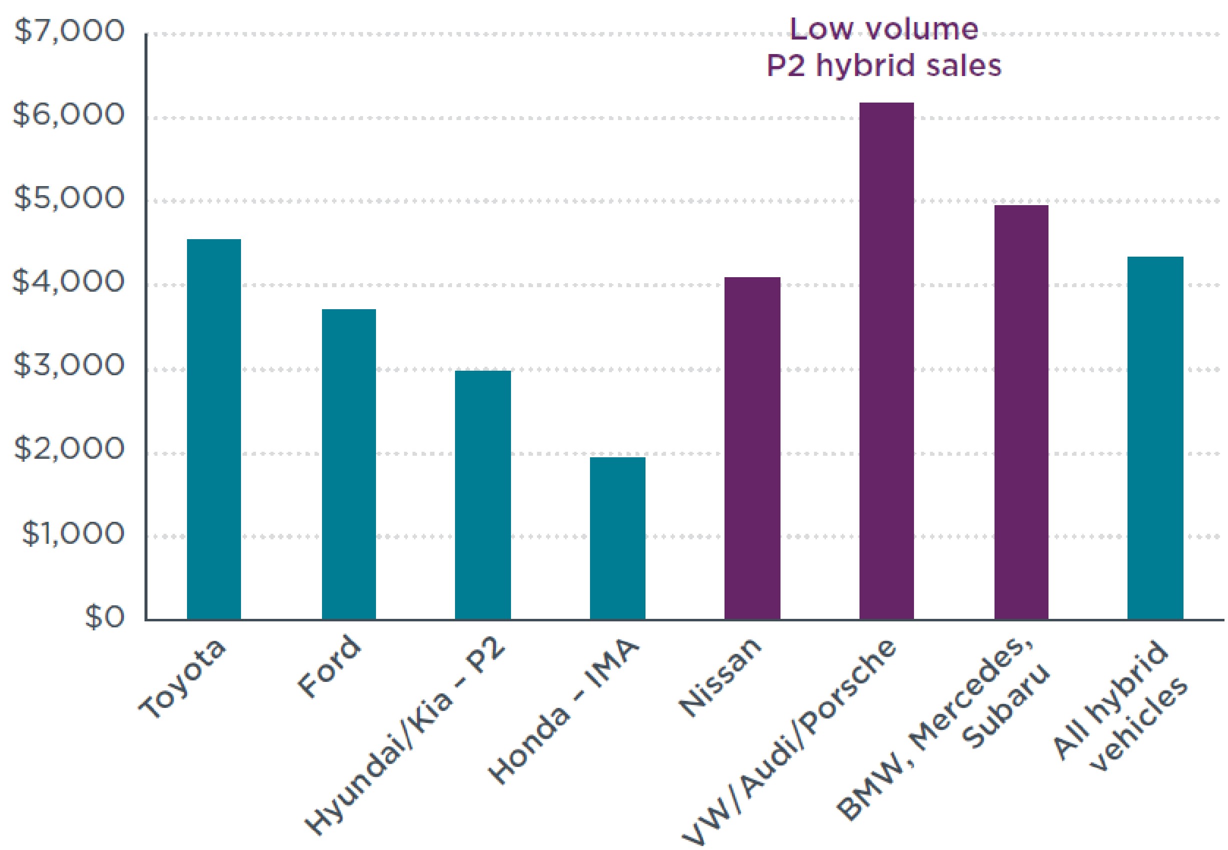

Figure 4-3: Incremental Retail Price of Hybrids in MY 2014

The typical cost-to-retail price ratio is 1.5, so that the cost of the PS hybrid which is used by Ford and Toyota is in the $2500 to $3000 range, in good agreement with the teardown-based

[7] Slowik, Pavlenko and Lutsey, "Assessment of Next Generation Electric Vehicle Technologies"' ICCT white paper, October 2016, available at www.theicct.org

[8] Vincentric Hybrid Analysis, executive summary, www.vincentric.com/Home/IndustryReports/HybridAnalysis October2014.aspx. Detailed results are available in PDF and Excel files, linked from the summary.

estimate. The cost of the P2 hybrid from Hyundai Kia would be $2250 which is lower than the TAR estimates, but Honda's IMA system is more akin to a mild hybrid system. Costs even for low volume and/or luxury models are not substantially higher, with the BMW/Mercedes/Subaru estimate equivalent to a $3300 cost for the P2 hybrid.

The other area where costs are very different in the PRIA is for mass reduction, which is surprising as both EPA and NHTSA relied on the same teardown studies to reach their conclusions. In fact, the PRIA uses the same study on the Honda Accord light-weighting that was used in the 2016 TAR but the costs have been changed significantly for unexplained reasons. The current PRIA shows average costs for mass reduction while earlier studies shoed the cost increment for each 5% mass reduction. With increasing incremental cost with increased mass reduction, average cost will always be lower than incremental cost. Figure 4-4 from the 2016 TAR shows the incremental cost of weight reduction, and it is unusual in that incremental cost decreases between 11% and 19% weight reduction but increases elsewhere.

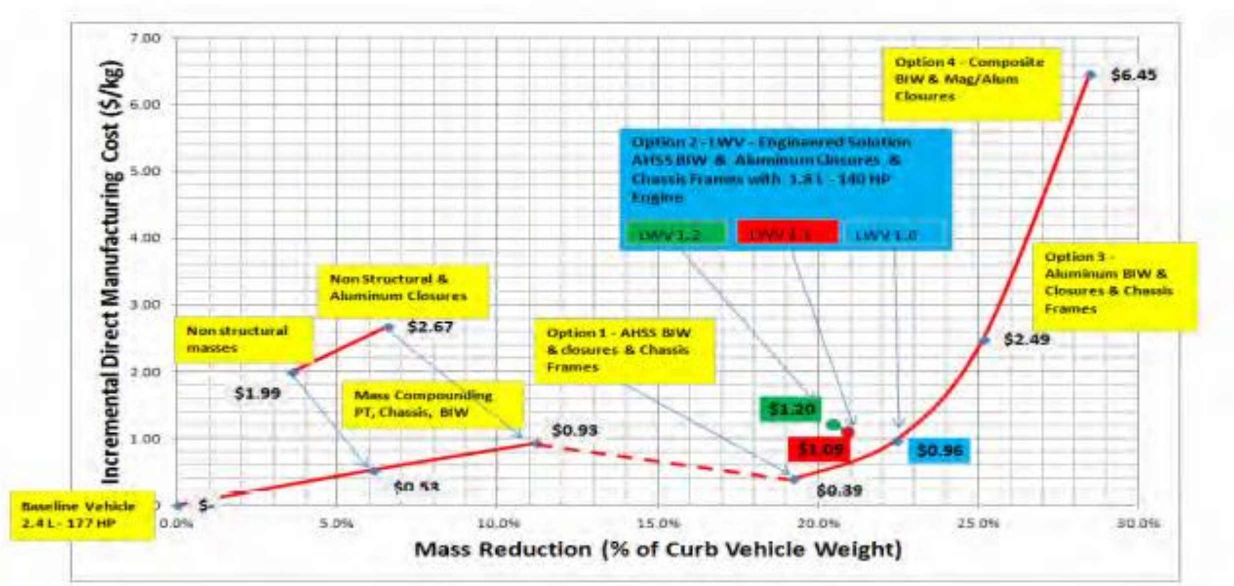

Figure 4-4: Incremental Costs of Mass Reduction from Honda Accord Study in 2016 TAR

The base Honda Accord weighed 1480 kg and each 1% represents a 14.8 kg reduction in weight. The incremental cost for the first 6.1 % weight reduction is $0.53/kg which translates to total cost of about $48 for a 90 kg weight reduction, while the next 5% costs $0.93/ kg, or a total cost of $71 for a 73 kg. weight reduction. Hence the 11.1% reduction in weight (163 kg) costs $119 for an average cost of $0.73/kg. However, the PRIA estimates that a 175 kg weight reduction has a cost of $536 (table 6-38 in the PRIA) but no explanation is provided for the very large cost difference.

In addition, NHTSA assumes that the “glider” (i.e., the vehicle minus engine and transmission) accounts for half the curb weight and the weight reductions apply only to the glider, not the powertrain. Powertrain weights are calculated separately for the forecast and the weight of the powertrain is assumed to stay constant for weight reduction less than 7.5%. The reasons for these assumptions are unclear as the teardown data for the Accord shows the glider accounts for over 78% of curb weight and other vehicles for which data is available show similar numbers, usually about 80% (the Honda engine has VVL which makes it a little heavier than other engines of similar displacement). Hence, the PRIA forecasts use cost data that are not in agreement with the study that they are purportedly based on, and limit absolute weight reduction severely with an incorrect estimate of glider weight and constant powertrain weight. The truck weight reduction cost data used in the PRIA are closer to the those cited in the study that they were based on, but still limit absolute weight reduction based on the 50% assumption of glider weight, even though the teardown data shows the glider is 73.6% of curb weight for the Chevy Silverado teardown study used as the basis for the truck cost estimates.

4.4 Critique of Technology Effectiveness Estimates

In general, the PRIA utilizes estimates of effectiveness for engine technologies that are generally quite similar to those developed for the 2016 TAR with the exception of cooled EGR. The PRIA shows zero benefit for this technology which is quite different from TAR’s estimate of 4 to 5% benefit. The zero estimate is inconsistent with the fact that some manufacturers such as Toyota and VW are already using it and it is unlikely that the technology would be in the market place with no benefit. However, as stated in previous sections, the technology is not included in the PRIA forecast or the TAR forecast and is not covered here. It should be noted that this another highly cost-effective technology that has been ignored in the PRIA. Other technologies ignored in the PRIA are the Miller cycle engine, the HCR2 (or ATK2) engine with cooled EGR and combinations of advanced cylinder deactivation (ADEAC) with turbo or HCR technology.

The technologies included in the PRIA where the estimates are quite different are

- Idle Stop Start
- 48V Mild Hybrid System
- 8-speed automatic transmission with friction reduction
- Aero drag reduction
- Low Rolling Resistance tires
- Mass Reduction

4.4.1 Idle Stop

The idle stop benefit listed for a midsize car in the PRIA is 1.8% and is similar to the 2012 TSD projection. In contrast to the 2012 projections of 1.8 to 2.4 percent effectiveness under EPA test cycles, the 2016 TAR states that other sources have suggested an average of 3.5 percent. The 2015 Ford Fusion 1.5L TGDI was available with and without a 12V stop-start option, and the difference in fuel economy between the two versions suggests an effectiveness of about 3.3 percent on a fuel consumption basis. The 2015 Mazda 3 is available with and without the Mazda i-ELOOP regenerative braking and stop-start system. A comparison of EPA fuel economy guide test data for this vehicle with and without the system suggests that its two-cycle GHG effectiveness is about 3.35 percent. Bosch has claimed[9] that newer systems which can shut the engine off during decelerations as well as idle can provide effectiveness of up to 6%. Both actual data and data from suppliers support the inclusion of a benefit of at least 3.3%, which is almost double the benefit in the PRIA.

4.4.2. 48V Mild Hybrid System

The effectiveness of the 48V mild hybrid belt alternator system has been estimated at only 5.3% in the PRIA for a midsize car, and this benefit is substantially below the effectiveness observed in the few models already marketed with such systems. The effectiveness of the mild hybrid system can be derived from vehicle test data if the same vehicle/engine combination was marketed with and without the mild hybrid system, and this was the case with a few models sold in 2013 and 2014. The 2015 National Academy of Sciences (NAS) report[10] estimated a 10 percent effectiveness for mild hybrid technology based upon the 11 percent fuel consumption reduction observed in the 2013 GM Malibu Eco compared to a conventional model with the same engine. This observed 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 Malibu's mild hybrid package which used a 115V system. 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. For an equivalent mass, 48V mild hybrid technology effectiveness will be slightly less than that of 100V+ mild hybrids. EPA fuel economy guide test data comparing the 2015 Mercedes-Benz E400 20kW120V P2 mild hybrid and the comparable E350 conventional vehicle indicated about 13 percent GHG effectiveness.

[9] H. Yilmaz, Bosch Chief Engineer –Gasoline Systems, "Bosch Powertrain Technologies", Presentation at DEER Conference 2012, available at https://www.energy.gov/sites/prod/files/2014/03/f8/deer12_yilmaz.pdf

[10] NAS, "Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2",The National Academy of Sciences Press, 2015

In a presentation on the effectiveness of the ADEAC system and the combined effectiveness of ADEAC and a 48V mild hybrid system, TULA Technologies[11] provided information on the cost and benefit of ADEAC and mild hybrid systems effectiveness and costs both singly and in combination, and Figure 4-5 shows the benefit of the 48V mild hybrid system as 11% fuel economy (10% fuel consumption) and the combined benefit of ADEAC +Mild Hybrid as 23% fuel economy (18.7% fuel consumption). It is not clear why the Autonomie modeling used in the PRIA produces such a low estimate of the effectiveness of mild hybrid systems. Even if the TULA presentation is regarded as optimistic about the effectiveness since they are developers of the technology, the EPA modeling results of 8 to 9% effectiveness appear reasonable in the light of what is observed from certification data.

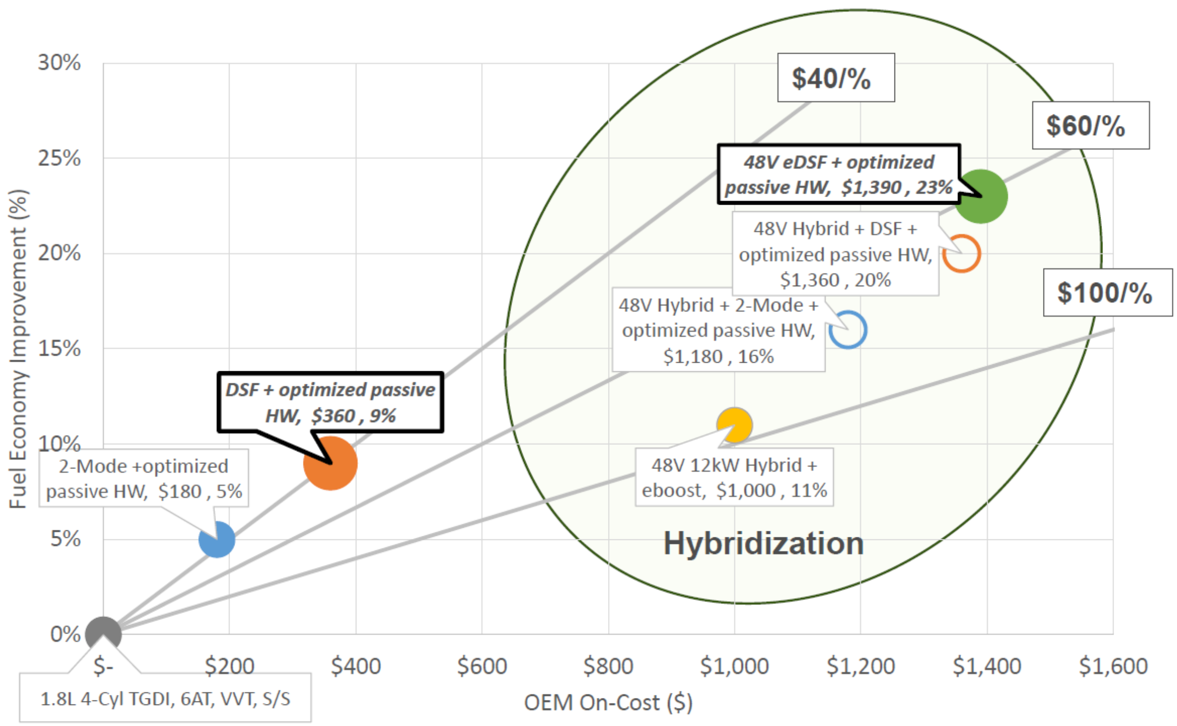

Figure 4-5: TULA Estimates of the Costs and Effectiveness of ADEAC and 48V Hybrid Technology

4.4.3. Eight+ Speed Automatic Transmission

The effects of the 8-speed (and 9/10 speed) automatics are also significantly understated in the PRIA. The effectiveness of multi-speed automatics in both the TAR and PRIA do not explicitly

[11] Tula Technologies Inc "Dynamic Skip Fire" presentation to the California Air Resources Board, September 28, 2016

account for the number of gears and the ratio spread. In a study for DOE[12], HDS provided more detailed analysis of the effects of several variables affecting the transmission benefit. It is difficult to estimate the effectiveness of specific transmission changes from actual vehicle data because other concurrent technology changes (some not publicly available) and differences in performance and test weight can bias the results. Only a few pairwise comparisons of near identical vehicles with two transmission options are available but even these may differ somewhat in acceleration performance due to the difference in ratio spreads.

The NAS 2015 report (ref.9) and a paper from transmission manufacturer ZF[13] show that the effect of increasing the number of gears for a given ratio spread is small and informal estimates from experts suggest that the benefit is on the order of 0.3% per gear, with ratio spreads in the 6 to 9 range, i.e., the effectiveness of 9 speed over a 6 speed with an equal ratio spread of 6.5 would be on the order of 0.9%. Of course, drivability and performance would be improved with the 9 speed. Researchers from GM provided details on a parametric study[14]of the effects of gear ratios, number of gear steps and loss levels so that each factor could be evaluated separately. The data presented suggests that going from 7 to 10 gear steps reduces CO2 emissions by about 3 g/km where the baseline is about 240 g/km or 1.25% for increasing the number of gears by 3, which is higher than the 0.3% per gear estimate but does not include the effect of any additional loss due to the higher number of gear steps. Based on this information and the benefit curves for ratio spread relative to a four-speed transmission, as well as published direct comparison data, the quadratic curve fit was:

$$\text{FC benefit \%} = 3.0^{*} (RS-4) - 0.27^{*} (RS-4)^2 + 0.3^{*}(N-4)$$

where RS is the ratio spread and N the number of gears, with 4 being both the ratio spread and number of gears of the hypothetical baseline four speed transmission. This equation indicates that the FC benefit is maximized at 9.5 ratio spread consistent with data from ZF.

HDS used the EPA estimate for the two friction reduction steps relative to the base 6- speed transmission and the early torque converter lockup benefit. Also, contrary to the assumptions in the TAR and PRIA, HDS estimated the benefit of active transmission warmup on the FTP cycle at about 0.5 % based on the difference between Bag 1 and Bag 3 fuel economy (cold start to fully warmed up start). Based on this HDS developed the following data (updated from the DOE

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[12] H-D Systems, "Updates on Fuel Economy Technologies for Meeting the 2025 CAFÉ Standards", Report to the DOE Office of Energy Systems and Policy Analysis, January 2017

[13] Gaertner, L. and Ebenhoch, M. "The ZF Automatic Transmission 9HP48 Transmission System, Design and Mechanical Parts", SAE Paper 2013-01-1276 April 2013

[14] Robinette, D. and Singh, T., ICE – Automatic Transmission Matching for Next Generation Power Transfer Technology, SAE Paper 2016-01-1099, April 2016

report for friction) as an approximation of the effectiveness for actual available transmissions relative to the 2016 Gen1 6 -speed with a ratio spread (RS) of 5.3 coupled to a conventional 4-valve DOHC PFI engine with VVT. The totals are in reasonable agreement with the observed pairwise comparison cases from MY 2016; for example, the Chrysler 200 with a 2.4L engine and A4 transmission was rated at 31.02MPG while the model with the A9 transmission at 36.59 MPG, an 18% increase while the table above predicts 11.3 (+6.0) or 17.3%. The Dodge Ram 5.7L V8 with an A6 transmission was rated at 20.44 MPG while the same model with the second generation ZF 8-speed at 22.31 MPG, a 9.1% while the table predicts an 9.9% increase. The Aisin 8-speed which is approximately equal to the ZF Gen 1 8-speed was claimed to be about 2% better in fuel consumption compared to the GM's second generation 6 -speed and the table shows a benefit of (6.5 – 4.6) or 1.9%. The assigned effectiveness of transmissions in the PRIA of 5 to 6% is half the maximum benefit that can be obtained, which we estimate at about 11%. It does not appear that the PRIA has considered idle-in-neutral and fast warmup technology, nor does it account for the ratio spread increase possible with modern transmissions.

		Ratio spread	Number of gears	Friction 1	Friction 2	Idle in Neutral	Early lockup	Active warmup	Total
Old 4-spd 4 RS		(3.44%)	(0.6%)	(1.0)	0	0	(1.0%)	-	(6.0%)
Gen 1 6-spd 5.3 RS		0	0	0	0	0	Ref.	0	Base
Gen 2 6-spd 6.3 RS		2.1%	0	2.5%	0	0	Ref.	0	4.6%
ZF Gen1 8-spd 7.2 RS		3.4%	0.6%	2.5%	0	0	Ref.	0	6.5%
ZF Gen2 8-spd 7.8 RS		4.3%	0.6%	2.5%	1.0%	1.0%	Ref.	0.5%	9.9%
ZF 9-spd 9.8 RS		4.9%	0.9%	2.5%	1.5%	1.0%	Ref.	0.5%	11.3%

4.4.4 Drag, Rolling Resistance and Mass Reduction

The effectiveness from both drag reduction and rolling resistance reduction are understated in the PRIA for two reasons. First, the modeling used in Autonomie utilizes assumptions inconsistent with the maximization of effectiveness of these two technologies. Second, the assumed improvements available in the 2017-2025 time frame do not even approach the lowest rolling resistance tires available today.

The Autonomie modeling assumes no engine change when drag and rolling resistance reductions are implemented, as well as no changes to the transmission gear ratios and axle ratios, which vary by transmission type but NOT by the tractive load. Over the combined city/highway cycle, aerodynamic drag and rolling resistance account for approximately 45% of the tractive load with inertia accounting for the remainder. (The percent of fuel consumption is lower because of fuel consumption during idle and deceleration, and fuel consumption from accessory loads which are independent of tractive loads). The PRIA has modeled a 20% reduction of both drag and rolling resistance which implies a reduction of tractive load by 45% x 20%, or 9%. A 10% weight reduction accounts for a 5.5% change in tractive load. In the latter case, the Autonomie model adjusts the engine size, but does not do so for the former case in spite of a larger change in tractive load. In the real world, aerodynamic drag reduction of 10% or more is usually accompanied by a reduction in the top gear ratios so that the engine can run at the same load but lower RPM on the highway, giving a quieter ride. Similarly, reduction in rolling resistance is accompanied by axle ratio adjustments so that the engine operates at about the same load but at lower RPM. The EPA ALPHA model adjusts for this effect, which accounts for the difference in benefit estimates shown below.

Technology		TAR Benefit	PRIA Benefit
Rolling Resistance -10%		2.2	1.54
Rolling Resistance -20%		4.4	3.06
Aero Drag -10%		2.1	1.51
Aero Drag -20%		4.3	3.03

The second factor that affects only rolling resistance reduction is demonstrated by the distribution of the rolling resistance coefficient (RRC) of vehicles in the 2016 baseline as published in the PRIA and reproduced in Figure 4-4.

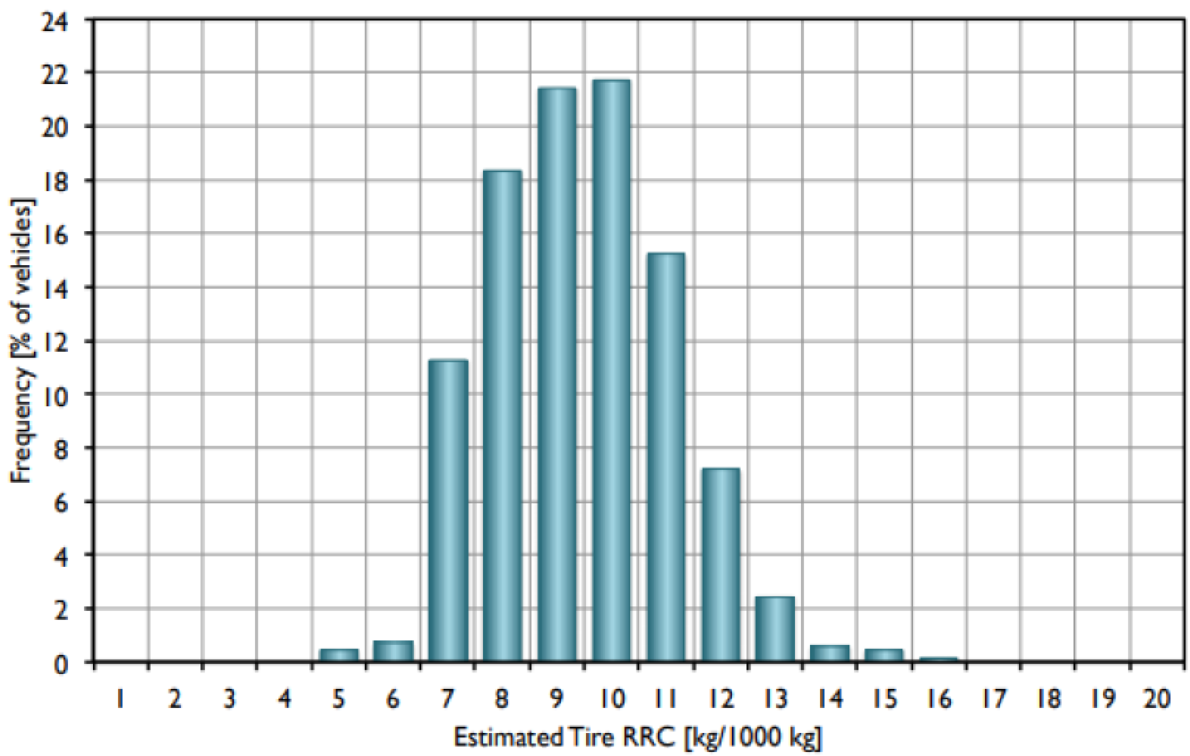

Figure 4-4: Distribution of Tire RRC in the 2016 fleet Shown in PRIA

Figure 4-4 shows there is a very significant fraction of the fleet with tire RRC above 10 kg/1000 kg, or 0.10 and a small percentage of vehicles with RRC already at 0.05 or 0.06. In their analysis, NHTSA assumed the baseline of 0.09 (which appears a little low but may be appropriate if the distribution was sales weighted) and had only two levels of rolling resistance reduction from the baseline – by 10% to 0.081 and 20% to 0.072. There are a significant number of vehicle models currently offered with tires at levels below 0.07 and it is unlikely that there will be no tire improvements over the next decade, and even current data shows that a ROLL30 technology, or 30% reduction to an RRC of 0.063, is possible and appropriate for MY2025. In addition, the baseline accounts for the distribution of tires blow 0.09 as 19% of vehicles in MY 2016 are modeled as having used ROLL10 and 25% of vehicles as having used ROLL20 in the base year, but there is no accounting for the ~25% of vehicles having RRC values 10 to 20% above the 0.09 RRC average. A stricter accounting of the baseline and, possibly setting specific lower limits for 2025 RRC by vehicle type (as done for aero drag in the PRIA) will show significant additional fleetwide effectiveness from RRC reduction which is a very cost-effective technology.

The main issue with the mass reduction analysis is that the PRIA applies the reduction to the glider weight which is assumed to be 50% of curb weight even though all the teardown studies including those sponsored by NHTSA show the glider weights for cars to be about 80% of curb weight. Engine weight reduction in the PRIA analysis is not easily accessible but we are aware of some assumptions in the Autonomie modeling that appear incorrect, such as the assumption that a turbocharged 4-cylinder engine weighs the same as a DOHV V6 engine with 1.5 times the 4 cylinder's displacement (in fact, it is usually 75 to 100 lbs. lighter). In addition, mass reduction assumes no reduction of powertrain weight for mass reduction levels of 2.5% and 5%. Mass reduction effectiveness therefore are somewhat more appropriate for reductions over 5% which apparently include some powertrain weight reduction. More transparency in the PRIA regarding powertrain weight changes will allow more detailed comment on engine weight assumptions used.

A second factor in the computation of mass reduction effectiveness is the baseline assignment of mass reduction levels to vehicles. The estimate of how much lighter a given 2016 vehicle is relative to the average for its "body type" and size was based on a regression analysis of curb weight against footprint, horsepower and driveline type (FWD, AWD, RWD) for conventional vehicles but also included electrified vehicles with different dummy variables in the same regression. Using the value of weight predicted by the regression for a vehicle of a given footprint and body style, the vehicle was assigned a level of weight reduction based on the ratio of the actual weight to predicted weight. The regression coefficients listed in Table 6-56 of the PRIA seem consistent for footprint, at 100 to 105 lbs./sq. ft. between the "2 box" and "3 box" body styles but the coefficient for HP is 1.22 lbs./HP for 3 box vehicles and 3.09 lb./HP for 2 box vehicles which is incorrect as they both use similar engines. Collinearity between footprint and HP or other effects caused by having electric vehicles (with electric motor HP ratings)in the regression data is the probable cause of these inconsistent coefficients for HP, but this cannot be confirmed without access to the same database used by NHTSA. Revisions to the regression could have a significant effect on the baseline assignment of vehicles, as the current assignment for vehicles like the 2016 Mazda MX5 as having the highest level of weight reduction technology (MR5)and the 2016 Chevy Mailbu as having MR4 technology appear incorrect as their curb weights are comparable to other similar MY 2016 vehicles in their respective class.

4.5 Chevy Equinox Example

The example of the Chevy Equinox in the PRIA is showcased in the following table to illustrate the effects of the incorrect assumptions employed in the PRIA. According to the PRIA analysis, the Equinox starts with VVT, SGDI, AT6, ROLL20 and AERO10 in 2016 with a base fuel economy of 34.1 mpg. Using the same starting point, the steps to 2025 in the PRIA are shown as are the equivalent steps using the LPM with only the addition of ROLL30 (at $80 over ROLL0 in 2025) technology being different between the two scenarios. The example illustrates the key points of this critique in Section 4.4 –1) the PRIA has similar costs for conventional technologies as the TAR, but high costs for the mild hybrid and 2) it underestimates the effectiveness of conventional technologies so that the 2018 redesign costs are similar but the fuel economy estimated by the LPM is 5.4% higher. This advantage in fuel economy persists and grows to 10% in 2025, where the same technology combinations are forecast to exceed the standards at a significantly lower cost. Removing the high cost P2 hybrid and MR5 weight reduction technologies enables the cost to be reduced to $2110 which is less than half the PRIA estimate, while still complying with the target of 51.7 mpg for 2025.

Table 4-6: Comparison of Chevy Equinox Example – TAR vs. PRIA

Year	PRIA MPG	PRIA COST	LPM MPG	TAR COST		TECHNOLOGY ADDED
2016	34.1	$43	34.1	BASE		VVT, SGDI, AT6, ROLL20, AERO10
2018	47.1	$3470	49.64	$2271		VVL, TURBO1, AT8 IACC, LDB, AERO20, BISG (LPM Includes HEG2, EFR2)
2021	47.6	$3070	NA	NA		AT10 (not in LPM)
2025	52.3	$5020	57.55	$4035		TURBO2, AT8, HEVP2, MR5
2025 Alt	NA	NA	52.2	$2110		Delete HEV P2 and MR5, add ROLL30

Even the numbers above for the LPM overstate the cost of compliance with the 2025 standard for this Equinox at 51.7 mpg. Off-cycle credits could allow reduction in the fuel economy targets to further reduce the technology requirement to comply with 2025 standards. As noted, the Chevy Equinox at a base fuel economy of 34.1 mpg is well below its technology potential as the 2016 Honda CR-V (also with a 2.4L engine and near similar size as the Equinox) was rated at 38.7 mpg, a 13.5% improvement over the Equinox. The lower weight of the CR-V and the use of the 2-step VVL in its engine would explain only about 8.5% of the difference, suggesting that the 2016 Equinox could have improved its fuel economy by 5% at no cost. In 2018, the Equinox was downsized and the CRV and Equinox are now very similar in weight, with both offering a 1.5L Turbo engine, but the CRV attains a fuel economy of 41.4 mpg to the Equinox' 38.2 mpg, an 8.4% advantage. The advantage is potentially due to the HCR + Turbo combination as well as the CVT used by Honda. The HCR +Turbo (or Miller cycle) is not considered in the PRIA as an available technology.

5 CONCLUSIONS

The proposed SAFE regulations would maintain Corporate Average Fuel Economy and GHG standards for the 2020 to 2026 period at levels equal to current requirements for 2020, instead of becoming more stringent over the 2021-2025 period per current regulations. The analysis supporting these regulations concludes that the per vehicle average retail price impact of meeting the proposed CAFE regulations is $700 while to price impact of meeting existing regulations is $2650, or a difference of $1950, and also finds that the 2025 current standards are not cost effective for the customer while the 2020 standards are cost effective. Due to the new analysis showing that manufacturers would meet current 2021 standard even under the proposed regulation, the comparison to earlier estimates of costs to comply with 2021 and 2025 estimates are appropriate. In 2016, EPA and NHTSA estimated the retail price impacts at $760 for meeting the 2021 standard and $1780 for meeting the 2025 standard. Hence, the new analysis shows a $60 lower cost for meeting the 2020 (or actually 2021) standard while showing significantly higher by $$870 cost for meeting 2025 standards.

Detailed analysis of the costs and effectiveness of technologies used to meet the 2021 and 2025 standards under the new analyses show that

- The costs of conventional technologies (i.e., non-electric) are very similar in the PRIA to earlier estimates for most (but not all) technologies. Costs are significantly higher in the PRIA only for mass reduction and the HCR2 engine compared to those from 2016.
- The costs for hybrid electric technologies in the PRIA are substantially higher than earlier estimates but the effectiveness are quite similar to or slightly higher than earlier estimates.
- The PRIA's costs for meeting 2021 standards are similar to earlier estimates because the standard can be attained primarily with the use of conventional technologies whose costs have not changed significantly. The $60 reduction in cost in the new analysis appears to be largely due to (inadvertent?) omission of the costs of engine friction reduction which appear to be included in the effectiveness but not the costs.
- Costs of meeting 2025 standards are much higher in the PRIA because more hybrid technology is required to meet the standard as a result of decreased effectiveness from conventional technology. The cost of hybrid technology is also much higher. The costs of hybrids do decline more sharply with time due to learning and scale in the PRIA analysis so that costs in calendar year 2030 are less different than in 2025.

An examination of conventional technologies whose effectiveness have been reduced in the new analysis show modeling assumptions that are not supported by available data. For instance, the estimates of mass reduction are assumed to apply to only the glider part of the vehicle and the weight of the powertrain is excluded from mass reduction in many cases. In addition, the glider is assumed to account for only half the curb weight of the vehicle. Data from EPA and NHTA's own studies show that the glider weight is ~80% of the curb weight, and the weight of the powertrain scales with the weight of the glider.

Drag reduction and tire rolling resistance technology is modeled without changes to the gear ratio or axle ratio to account for the reduced tractive energy requirement, thereby discounting effectiveness. The model also specifies conventional engine technology pathways that are mutually exclusive and are called Turbo, High Compression ratio and Advanced Cylinder Deactivation, but does not allow combinations of these pathways that can provide cost effective reductions in fuel consumption and CO_2. These technology combinations have already been introduced in a few vehicle models in 2018, making such assumptions unsupportable. The table below summarizes the extent of reduction in effectiveness from conventional technologies in the new analysis compared to previous estimates documented by EPA, NAS and data from actual vehicle tests

Technology		PRIA Estimate	Correct Estimate	Justification for correct estimate
Stop-start Systems		1.8%	2.8 - 3.3%	From vehicle test data
Mild Hybrid		5.35%	9.0%	From vehicle test data
Advanced 8/9 spd. Trans.		7.6 to 8%	10 to 11%	Data from FCA models
Aero 20		3.0%	4.3%	No Gear/Axle ratio adjustment in PRIA analysis
Roll 20		3.1%	4.4%	No Gear/Axle ratio adjustment in PRIA analysis
Mass Reduction 5		6.9%	10.4%	Glider weight assumption error
HCR2		Not used	~19%	From 2018 Camry data
Miller Cycle		Not used	4 to 5% over turbo	From VW/Honda data
ADEAC + 48V Hybrid		Not used	~20%	Tula Technologies/ Delphi data

The sources of new cost data are not documented in the PRIA. Costs of all hybrid technology are higher by a factor of 2 to 2.5 in calendar year 2016, the baseline year, compared to earlier estimates (costs come down in future years). Hybrids of all types have been in the market for a decade or more and costs have been estimated for all hybrids based on actual teardown studies (sponsored by EPA and the European Union). Cost data has also been publicly discussed by suppliers of hybrid systems and costs can be estimated from actual retail prices. The teardown studies cost data, the supplier data and the retail price data provide mostly consistent estimates of hybrid system costs that contradict the new estimates of cost.

While the technology costs and effectiveness account for much of the differences between earlier analyses and the new analysis, there are a number of assumptions in the Volpe CAFE model's baseline and model logic for when technology can be adopted which also increase costs of compliance. To avoid double counting technology effectiveness and costs, the technologies present in each vehicle model in 2016 is estimated and the effectiveness of new technologies applied as percentage reductions in fuel consumption from the baseline value. However, the baseline estimates of technology penetration are not reconciled across manufacturers so the two manufacturers can have technologically identical products but with significantly different baseline fuel economy. In the model, the baseline differences in fuel economy are carried for all future years and this exaggerates the differences in technology adoption requirements and costs.

The CAFE model logic also constrains most technology introduction to years when the entire vehicle is being redesigned or refreshed. The actual data on technology introductions in the market show that no such constraint exists in the real world. In addition, the CAFÉ model also has complex rules on engine and transmission adoption and how they propagate through different vehicle models in the fleet of a specific manufacturer. These rules are not supported by any actual data and it is not clear how they are implemented for Asian manufacturers whose model lines are sold globally. These assumptions result in unnecessary distortion in technology paths and may bias results of costs for different manufacturers.

Finally, the PRIA utilizes an example of a Chevy Equinox small SUV to illustrate the technology adoption path and cost of meeting 2025 standards. The vehicle has a fuel economy of 34.1 mpg in 2016 and attains a fuel economy of 52.3 mpg for a cost of $5020 in 2025. Calculations using the EPA lumped parameter model and previous cost data show that the same technology assumptions should lead to a fuel economy of 57.55mpg for a cost $4035. Removing the least cost-effective technology to closely match the 52.3 mpg results in an estimate of attaining 52.2 mpg for a cost of $2110, which is less than half the cost modeled in the PRIA. This example illustrates how the reduced effectiveness estimates for conventional technology and the higher cost estimates for hybrids in the 2018 PRIA combine to provide an unrealistic estimate for the cost of compliance.