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Roush Industries, Inc.
Roush Engineering
Gary W. Rogers
Vice President, Advanced Technology

Technical Review of:

The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks

Final Report

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Roush Industries, Inc.

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About the Author

Gary W. Rogers has been Vice President of Advanced Technology for Roush Industries since 2014. Roush Industries is privately-held with over 4000 employees who perform engineering research, design, development, testing, precision machining and flexible, low volume manufacturing and assembly for the automotive and commercial vehicle industries. Roush also emission certifies, sells and warrants Roush-branded high-performance vehicles and offers alternative-fueled conversion systems for commercial vehicles and buses which include propane, natural gas and electric powertrains.

Prior to joining Roush, Mr. Rogers was the founding president of FEV North America, Inc. and managed this U.S. subsidiary of FEV GmbH for almost 29 years until his retirement in 2013. FEV is a highly-regarded, powertrain and vehicle engineering research, design, development and testing company which supports the worldwide automotive, commercial vehicle, marine and stationary power generation industries. During his tenure, FEV supported EPA in advanced technology demonstrations and conducted numerous manufacturing cost studies and tear-down analyses which are referenced in the 2016 Technology Assessment Report for the Final Rule Making for MY2021-2025 Passenger Cars and Light Trucks.

Specific to the assessment of technology for increasing fuel economy and reduction of greenhouse gas, Mr. Rogers has served on several National Academies boards and committees, and coauthored resulting reports. They include:

- *Board on Energy & Environmental Systems, The National Academies, (2012-2018)*
- *Committee for the Assessment of Fuel Economy Technologies for Medium and Heavy-Duty Vehicles, National Research Council, The National Academies (2013-2018)*
- *Committee for the Assessment of Technologies for Improving Light-Duty Vehicle Fuel Economy, National Research Council, National Academy of Sciences (2007-2009)*
- *Committee on Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Research Council, National Academy of Sciences (2001– 2002)*

In addition, Mr. Rogers has served as a technical reviewer on two (2) reports of importance for the subject of this technical assessment:

- *Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2, National Research Council, The National Academy of Sciences (2015)*
- *Transitions to Alternative Vehicles and Fuels, National Research Council, The National Academy of Sciences (2013)*

Table of Contents

Technical Review of:

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Final Report

Executive Summary

Introduction

Gary W. Rogers, and Roush Industries, Inc., were retained by the California Department of Justice, Office of the Attorney General, to conduct a technical review of The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks, (83 Fed. Reg. 42,986, Aug. 24, 2018) hereafter referred to as the "Federal Proposal."

Roush has completed a technical review of the Federal Proposal, including the 2018 Notice of Proposed Rulemaking (NPRM), the Preliminary Regulatory Impact Analysis (2018 PRIA), and other associated vehicle simulations, published CAFE modeling results and related appendices. We have also examined the 2016 Draft Technical Assessment Report (2016 Draft TAR) submitted by EPA and NHTSA (hereafter referred to as "the Agencies") as part of the midterm evaluation of light-duty vehicle final rule.

Review of the 2018 Preliminary Regulatory Impact Analysis

Our assessment finds the 2018 PRIA projected average costs for technology implementation to achieve the existing standards to be significantly overstated and in conflict with the 2016 Draft TAR cost estimates generated by the Agencies only two years earlier, as shown in Table ES-1. Further, we find the 2016 Draft TAR analyses of cost and incremental fuel economy improvement to achieve the model year MY2025 standard of the augural CAFE and tailpipe carbon dioxide (CO_2)[1] standards to be consistent with Roush estimates and other published data.

Predicted Price Increase for MY2025 Vehicle from MY2021 to Comply with CAFE/CO_2	2016 TAR CAFE (2016$) (MY2028)[2]	2016 TAR CO_2 (2016$)	2018 PRIA CAFE (2016$)	2018 PRIA CO_2 (2016$)
2025 Passenger Car	$1,111	$707	$1,730	$1,750
2025 Light Truck	$1,246	$1,099	$2,220	$1,960
2025 Combined	$1,174	$894	$1,960	$1,850

Table ES-1: Comparison of 2016 Draft TAR and 2018 PRIA Estimated Compliance Costs

[1] The existing GHG emissions standards cover carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4); this report focuses on the tailpipe CO_2 emission standards.

[2] Due to credit carry-over features in CAFE, the true costs to comply with MY2025 are not realized until MY2028. Such noncompliance is not permitted in CO_2 emission standards.

Within the scope of effort conducted to date, we found several reasons for the excessively-high predicted fleet-average costs necessary to comply with the existing standards. They include:

1. *Understated Incremental Technology Effectiveness*: In many cases, the estimated level of improvement for individual technology increments are significantly understated due to inaccurate engine and transmission performance maps or the lack of vehicle system optimization and calibration which are the state-of-the-art in vehicle system modeling.

2. *Understated (or Uncalculated) Synergistic Benefits*: In other cases, we found inaccurate or complete exclusion of synergistic benefits. For example, while maintaining constant vehicle performance, varying engine characteristics allow other vehicle systems, such as gear ratio spreads or transmission shift strategies to be optimized for improved fuel economy. These benefits were often not modeled or calculated in the Federal Proposal.

3. *Exclusion of Incremental Technologies Already in Production*: Our review identified several beneficial technologies which were identified, but not utilized in technology pathways, such as second generation, high compression ratio engines with cooled EGR. In another case, the use of Miller-cycle in high compression ratio (CR), turbocharged engines was excluded completely, despite being in production by VW (1.5L) since 2017[3].

4. *Overstated Costs for Incremental Benefits*: In other cases, the estimated cost for incremental technology improvement is significantly overstated, without explanation or reference. This is particularly true for Atkinson-cycle high compression ratio engines, and both mild and strong hybrids due to uncharacteristically high battery costs.[4]

5. *Constrained Technology Pathways*: Functional constraints exist in the CAFE model which cause over-compliance in some scenarios, under-compliance in others, artificial product development cadence and prescribed technology pathways that force illogical technology application. For example, the CAFE model forces application of cooled EGR in the pathway higher CR engines with almost no fuel economy improvement predicted. Coupled with an overly-stated cost, this creates a very illogical, cost-inefficient pathway.

Roush Independent Analysis of Existing Standard-Compliance Pathways

To help quantify the effects the five above-stated issues have on compliance cost exaggeration, Roush conducted independent fuel economy (FE) technology pathway modeling for two (2) vehicle classes: 1) Small SUV; and 2) Full-size Pickup.

Roush developed state-of-the-art engine maps based on production engines, which were adapted using the automotive industry-accepted GT-Power simulation code. We then developed transmission maps to maximize FE using industry-accepted optimization strategies within the GT-Drive vehicle simulation code, while maintaining constant vehicle performance. Finally, we evaluated different engine technologies, varied gear ratios, shift strategies, vehicle weight,

[3] "Volkswagen Millerized 1.5L TSI ACT BlueMotion gasoline engine offers diesel-like fuel economy" Green Car Congress, March 19, 2018. (https://www.greencarcongress.com/2018/03/20180319-vw15.html)
[4] NHTSA and EPA, The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Year 2021 – 2026 Passenger Cars and Light Trucks, Preliminary Regulatory Impact Analysis, Page 1105, Tables 9-3 and 9-4, July 2018

rolling resistance and drag coefficients to predict FE and ultimately formulated logical, cost effective technology pathways to achieve MY 2025 existing standards.

Small SUV Compliance with MY2025 Existing Standards

To begin the analysis, the 2018 Mazda CX-5 small SUV was chosen as a vehicle against which to calibrate our model. Also, due to the use of a high CR Atkinson-cycle engine in its SkyActiv[5] powertrain, we considered this a good example of technology progression in SUVs to date.

Next, we chose the Toyota Rav4 as a MY2016 test case following the 2018 PRIA baseline vehicle logic (DOHC, PFI, VVT, 6AT) and developed a logical, cost-effective technology pathway. We followed industry-accepted full vehicle system calibration and FE optimization techniques at constant vehicle performance to determine the incremental FE improvements necessary for CAFE compliance. The MY2025 augural target fuel economy for this vehicle, based upon its footprint, is 58.0 mpg, combined city-highway.

The pathway chosen by the 2018 PRIA analysis selected a high CR, DI engine in MY2020 with an 8AT, full hybrid-electric powertrain, and reductions of 15% weight, 20% rolling and 20% aero drag to achieve 58 mpg at a cost of $4,553.00. When technology-learning factors are considered, the estimated cost for compliance in MY2025 is $4,422.00 for 2018 PRIA.

By comparison, the cost-effective pathway developed by Roush employs a high CR engine in MY2020 but extends the engine choice to a higher CR engine with cooled EGR and a 48V BISG which is much more cost effective than a full hybrid electric powertrain. Combined with similar weight, rolling resistance and weight reduction, the Roush pathway achieves 57.9 mpg at a cost of $1,767.00 in MY2025. These results are obtained by choosing logical, cost-effective technologies and developing powertrain, transmission and vehicle system technology maps.

This engine technology pathway replicates the engine used in the MY2018 Mazda CX-5 (HCR1) plus a 48V BISG, such as that applied in the MY2019 Jeep Wrangler with 2.0L turbocharged engine. The evolution to HCR2 with cooled EGR, such as the Toyota Dynamic Force Engines produces a vehicle technology package that is much more cost-effective than the 2018 PRIA.

Full-Size Pickup Compliance with MY2025 Existing Standards

As in the small SUV analytical procedure, we first chose a vehicle against which to calibrate our model; in this case a 2016 Ram 1500 pickup with a 3.6L V6 NA engine. Based upon the high cost-effectiveness of the high CR engines and BISG shown in the small SUV case, we applied an HCR1 engine, 48V BISG, an even higher CR with cooled EGR (HCR2) and cylinder deactivation (DEAC). We combined this pathway with gear ratio and shift strategy optimization, reduced weight, improved aero and rolling resistance, all while keeping constant performance.

The MY2025 augural target FE for this vehicle is 33.3 mpg, combined city-highway cycle. The 2018 PRIA CAFE model prediction exceeds this target, reaching 35.8 mpg, at a cost of $3,371.87 in MY2025, with a pathway with a downsized turbocharged DI engine with cooled EGR and a 48V BISG.

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[5] https://insidemazda.mazdausa.com/press-release/mazdas-turbocharged-skyactiv-engine-wins-2017-wards-10-best-engines-award/

However, a much more cost-effective path is possible as shown by the Roush-proposed NA, high CR engine, combined with a BISG, but modeled with accurate effectiveness values and reasonable cost. The Roush proposal achieves even greater FE, 38.2 mpg by MY2025, and exceed the augural standards each year from MY2016 to MY2025. At a projected cost of $2,359.52 in MY2025, the Roush proposal is over $1,000.00 less than the 2018 PRIA analysis (a projected cost reduction of over 30%) and FE which exceeds the MY2025 target by 15%.

Conclusions

Roush has shown that the use of logical, unrestricted, technology pathways, with incremental benefits supported by industry-accepted vehicle simulation and dynamic system optimization and calibration, together with publicly-defensible costs, allows cost-effective solutions to achieve target fuel economy levels which meet MY2025 existing standards.

It is also important to note that all the technology steps chosen to achieve MY2025 target CAFE fuel economy levels for our two test cases (Small SUV and Full-Size Pickup) are currently in production within various platforms across different manufacturers.   Therefore, their inclusion in our exemplar pathways represents a very viable product evolution cycle

Of primary importance is establishing accurate engine maps, transmission maps, fuel economy optimizing shift strategies, reestablishing transmission gear ratios and shift points as powertrain and vehicle characteristics change (such as addition of mild hybrid system) and defining technology pathway algorithms that are consistent with normal product development constraints. Since we are, in most cases, considering small, incremental improvements in efficiency, accurate engineering analyses are critical is determining technical viability to achieve future fuel economy targets.

The development of reasonable cost estimates is also important to understand the probability of commercial success for future technology approaches. However, variability in worldwide manufacturing and financial markets, the impact of foreign regulatory climates on new technology cadence (such as vehicle electrification in China) and other variables make accurate prediction of component- or system-level costs very challenging. Furthermore, continued advancements in traditional technology, combined with supplier willingness to reduce margin with increasing competition, will also influence future technology pricing.

We have not performed a complete fleet-compliance simulation. However, we have identified many areas for improvement which, if enacted, would likely produce significantly different results in the overall fleet CAFE compliance assessment.

Technical Review of:

The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks

Final Report

1.0 Introduction

Gary W. Rogers, and Roush Industries, Inc., were retained by the California Department of Justice, Office of the Attorney General, to conduct a technical review of The Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule for Model Years 2021-2026 Passenger Cars and Light Trucks, (83 Fed. Reg. 42,986, Aug. 24, 2018) hereafter referred to as the "Federal Proposal."

The Federal Proposal presents several options to relax the greenhouse gas (GHG) emissions and corporate average fuel economy (CAFE) standards for model years (MY) 2021 – 2026 with a primary recommendation to hold the levels constant from MY2020 onward. This rollback represents a significant relaxation of the existing greenhouse gas emissions standards, the existing fuel economy standards for MY2021, and the so-called "augural" standards for MY2022 – MY2026 (hereafter referred to as the existing GHG emissions standards or augural CAFE standards, respectively, or collectively as the existing standards).

Roush has completed a technical review of the Federal Proposal, including the 2018 Notice of Proposed Rulemaking (NPRM), the Preliminary Regulatory Impact Analysis (2018 PRIA), and other associated vehicle simulation analyses, published CAFE modeling results and related appendices.

We have also examined the 2016 Draft Technical Assessment Report (2016 Draft TAR) submitted by the Environmental Protection Agency and the National Highway Traffic Safety Administration (hereafter referred to as "the Agencies") as part of the midterm evaluation of light-duty vehicle final rule and the 2015 National Research Council report titled "Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles" (2015 NRC). In addition, we have reviewed the 2010 EPA Regulatory Impact Analysis (2010 RIA) for the Agencies' final rulemaking for model years 2012-2016.

2.0 Review of the 2018 Preliminary Regulatory Impact Analysis

Our assessment finds the 2018 PRIA projected average costs for technology implementation to achieve the augural MY2022-MY2025 light-duty vehicle standards to be significantly overstated and in conflict with the 2016 Draft TAR cost estimates generated by the Agencies only two years earlier. Further, we find the 2016 Draft TAR analyses of cost and incremental fuel economy improvement of incremental vehicle subsystems to achieve MY2025 CAFE and CO_2 standards to be consistent with Roush estimates and other published data.

Predicted Price Increase for MY2025 Vehicle from MY2021 to Comply with CAFE/CO_2	2016 TAR CAFE (2016$) (MY2028)[6]	2016 TAR CO_2 (2016$)	2018 PRIA CAFE (2016$)	2018 PRIA CO_2 (2016$)
2025 Passenger Car	$1,111	$707	$1,730	$1,750
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Table 1: Comparison of 2016 Draft TAR and 2018 PRIA Estimated Compliance Costs

Within the scope of effort conducted to date, we found several reasons for the excessively-high predicted fleet-average costs necessary to comply with the existing standards. They include:

1. *Understated Incremental Technology Effectiveness*: In many cases, the estimated level of improvement for individual technology increments are significantly understated, because of inaccurate engine and transmission performance maps, the lack of vehicle system optimization and calibration which are the state-of-the-art in vehicle system modeling, or other background information that has not been disclosed. By example, the fuel economy benefit of start-stop with torque assist from a Belt Integrated Starter Generator (BISG) is estimated at about 5%, whereas accurate system modeling and a 48V BISG in production (MY2019 Ram Truck) show improvements over 10%[7].

2. *Understated (or Uncalculated) Synergistic Benefits*: In other cases, we found incorrect application, or exclusion, of synergistic benefits, caused by lack of transient system modeling. For example, while maintaining constant vehicle performance, changing engine characteristics can allow other vehicle systems, such as gear ratio spreads, differential gear ratios, or transmission shift strategies to be optimized for improved fuel economy. These benefits were often not modeled or calculated in the Federal Proposal.

3. *Exclusion of Incremental Technologies Already in Production*: Our review identified several incremental technologies which were identified, but not utilized in technology pathways, such as second generation, high compression ratio engines with cooled EGR for knock mitigation. In another example, the use of Miller-cycle features in high compression ratio, turbocharged engines was excluded completely, even though VW introduced in a turbocharged engine with Miller-cycle valve timing in MY2017[8].

4. *Overstated Costs for Incremental Benefits*: In other cases, the estimated cost for incremental technology improvement is significantly overstated, without explanation or reference. This is particularly true for mild hybrids (48V Belt-Integrated Starter Generators) and strong hybrids (high voltage, parallel hybrid such as Toyota Prius) where estimated costs are more than 2x the estimated costs in the 2016 Draft TAR.

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[6] Due to credit carry-over features in CAFE, the true costs to comply with MY2025 are not realized until MY2028. Such noncompliance is not permitted in CO_2 emission standards.

[7] "First Drive: 2019 Ram 1500 eTorque Mild Hybrid," Truck Trend, September 11, 2018, (http://www.trucktrend.com/features/1809-first-drive-2019-ram-1500-etorque-mild-hybrid)

[8] "Volkswagen Millerized 1.5L TSI ACT BlueMotion gasoline engine offers diesel-like fuel economy" Green Car Congress, March 19, 2018. (https://www.greencarcongress.com/2018/03/20180319-vw15.html)

5. *Constrained Technology Pathways*: Functional constraints are present in the CAFE model which result in over-compliance in some scenarios, under-compliance in others, and artificial cadence in product development cycles and prescribed step-wise technology paths that force the application of technologies in illogical ways. For example, the CAFE model forces application of cooled exhaust gas recirculation within the evolution of higher compression ratio engines. However, there is almost no fuel economy improvement predicted. Coupled with an excessively-high approximated cost, this creates a very illogical, cost-inefficient pathway.

In fact, based upon the rapidly-falling costs of batteries and other hybrid-electric components observed between calendar year (CY)2016 and CY2018[9], the 2016 Draft TAR projections for an "average vehicle" across the U.S. annual new vehicle sales between MY2021 and MY2025 are likely somewhat overstated. However, the battery and hybrid-related component costs in the 2018 PRIA are excessively high.

Comparison of incremental fuel economy improvements for technology features between 2015 NRC and 2016 Draft TAR found the correlation to be quite good and the incremental technology fuel economy improvement values very consistent with Roush estimates. However, a direct comparison for all fleet classes, projected vehicle types and fleet mix was not performed.

The 2016 Draft TAR included a summary table (Table 2) of bundled technology packages and their estimated improvements in fuel consumption for application to different vehicle classes.[10] The table also provides a comparison to the analyses for the original 2012 Rule which were conducted in 2009. Effectiveness is defined as the percent improvement in fuel economy for a given technology package over a baseline engine configuration. The 2012 final rule making (FRM) is compared to the 2016 Draft TAR.

Our assessment of the 2018 PRIA analysis has identified many technical errors, improper assumptions and unusual analytical model boundary conditions which do not follow normal industry practices. This is likely due to technology path application logic which controls how incremental fuel economy (FE) improvement factors and their associated costs are chosen.

Table 5.64 FRM to Draft TAR Engine Technology Package Effectiveness Comparison

Engine Technology Package	Small Car FRM - TAR	Standard Car FRM - TAR	Large Car FRM - TAR	Small MPV FRM - TAR	Large MPV FRM - TAR	Truck FRM - TAR
PFI DOHC + VVT	4.1 - 4.1	5.2 - 5.2	5.5 - 5.5	4.1 - 4.1	5.1 - 5.1	4.9 - 4.9
SGDI DOHC + VVT	5.6 - 5.6	6.6 - 6.6	6.9 - 6.9	5.5 - 5.5	6.6 - 6.6	6.3 - 6.3
SGDI DOHC + VVT + DEAC + EFR1	10.5 - 9.9	12.8 - 12.1	13.5 - 12.7	10.4 - 9.8	12.8 - 12.0	12.1 - 11.4
18 Bar BMEP Turbo + SGDI	12.2 - 10.1	14.2 - 11.5	14.9 - 11.9	12.1 - 10.0	14.2 - 11.4	13.6 - 11.1
Atkinson + VVT + SGDI + EFR2	NA - 11.7	NA - 12.9	NA - 13.3	NA - 11.7	NA - 12.9	NA - 12.6
Atkinson + VVT + SGDI + CEGR + EFR2	NA - 19.3	NA - 19.4	NA - 19.5	NA - 19.3	NA - 19.4	NA - 19.4
24 Bar BMEP Turbo + SGDI + CEGR	19.4 - 17.2	22.1 - 19.1	23.0 - 19.7	19.3 - 17.1	22.1 - 19.1	21.3 - 18.6
Miller + SGDI + CEGR	NA - 23.0	NA - 23.3	NA - 23.4	NA - 23.0	NA - 23.3	NA - 23.2

Table 2: FRM to Draft TAR Engine Technology Package Effectiveness Comparison

[9] "USABC Cost Model – 2018," U.S. Advanced Battery Consortium, LLC, October 22, 2018, (http://www.uscar.org/guest/article_view.php?articles_id=143)

[10] Table 5.64, EPA and NHTSA, Draft Technical Assessment Report, 2016

We found, in some cases, unreasonable component and subsystem costs, inaccurate incremental FE improvement estimations, and likely improperly-generated technology pathways. These errors result in an over prediction of aggregated individual subsystem costs. In other cases, the understated incremental FE improvements for individual technology steps requires an excessive number to technology increments to achieve fuel economy targets. Such factors will result in overprediction of costs to comply with relevant CAFE and CO_2 standards.

2.1 Vehicle Modeling

Our review of the vehicle modeling approach employed in the 2018 PRIA to predict individual vehicle FE has identified a significant number of errors. Some lead to over prediction of FE improvement while other errors result in under prediction which influences incremental selection. Important, however, is that, while utilizing these inputs, the incremental selection algorithm was observed to produce unrealistic technology pathways, in many cases.

In other cases, the finally-predicted, individual vehicle FE, after all technology enhancements are applied, appears somewhat reasonable, due to opportunistically offsetting errors. However, the selection algorithm produces unrealistic pathways, that very significantly affect 2021-2025 projected compliance costs.

Examples:

1. *Engine Maps – No Fuel Consumption Penalty at High Load*

   Several of the base engine maps used in the 2018 PRIA analyses exhibit maximum thermal efficiency (lowest fuel consumption) at 2000-3000 rpm and at maximum load, which is unrealistic for normal passenger vehicle engines. Such maps will overpredict fuel economy for extremely down-sized applications (very small engine in a heavy vehicle). This is because there is no fuel economy penalty for running the engine at high loads point where, in reality, BSFC is high due to retarding spark timing to prevent knocking and fuel enrichment to reduce exhaust temperatures to protect exhaust valves and turbocharger components.

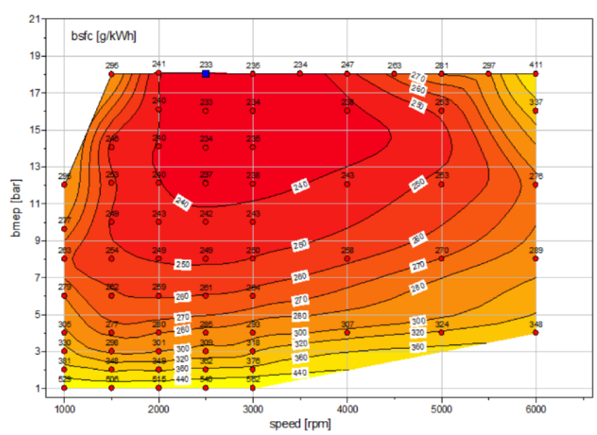

Figure 1: BSFC map for 2018 PRIA_Eng12 (93 Octane)

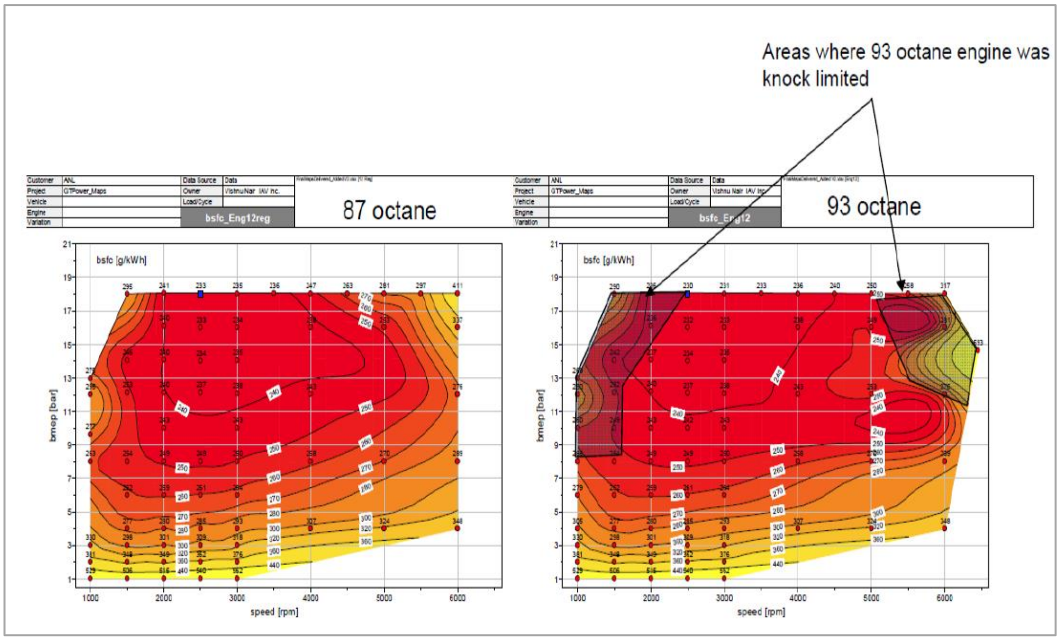

Figure 2: PRIA_Eng 12 (1.6 liter Turbo DI with Dual VVT and intake VVL) on 87 and 93 octane fuel

2. *Engine Maps – Variation in Cylinder Size*

   The engines modelled and used in the 2018 PRIA analyses range from a 2.0L, 4-cylinder to a 1.2L, 4-cylinder and a 1.0L, 3-cylinder. Within these configurations, the size of the cylinder varies from 500cc to 300cc. These variations in combustion chamber size would significantly alter combustion, heat transfer (small cylinders have high surface-to-volume ratio and higher heat transfer losses), knocking tolerance and other important operating parameters. Therefore, a more accurate simulation, which would improve incremental FE improvement, should maintain a 500cc cylinder displacement and vary the number of cylinders or expected fuel consumption maps.

3. *Engine Maps – Continuously Variable Valve Lift*

   In the 2018 PRIA engine examples, the base turbocharged engine is assumed to have VVL. With a turbocharged engine, the benefit of VVL over dual VVT is limited. Accordingly, almost all vehicle manufacturers use lower-cost Dual VVT systems in their turbocharged engines. The base turbocharged engine assumption is unrealistic with correspondingly high cost, which, if corrected, would allow appropriate technology pathways to be used.

4. *Engine Maps – Effect of Cooled Exhaust Gas Recirculation*

   The 2018 PRIA analysis applies cooled EGR to turbocharged engines in an extremely narrow window at high engine speed and high load. The 2018 PRIA modeling erroneously excludes the application of cooled EGR in engine operating modes that highly influence overall vehicle fuel economy. This exclusion of the benefits associated with knock mitigation and reduced enrichment significantly understates incremental improvement. The, Mazda 2.5L turbocharged SkyActiv engine exemplifies a wider-range cooled EGR strategy.

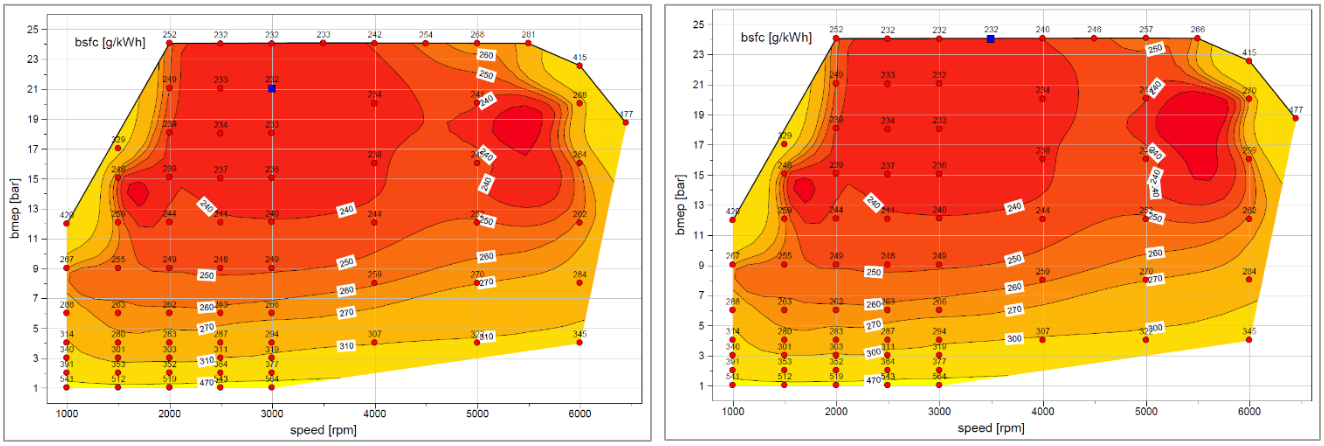

Figure 3: PRIA_Eng13 and -Eng14, downsized 1.2 liter with (left) and without (right) cooled EGR

5. *Engine Maps – Skip-Fire Variable Displacement*

The 2018 PRIA analysis does not properly consider the very cost-effective benefits of skip-fire technology which produces the net effect of variable displacement at very low cost. Due to extremely high estimated cost ($1,250.00 in MY2016), the benefits of this technology will likely not be chosen in any reasonable technology pathway. If included, the predicted cost for that pathway will be overestimated by $750.00 - $1,000.00.

6. *Engine Maps – Turbocharging plus Miller-Cycle*

The 2018 PRIA analysis does not consider the combination of turbocharging and Miller-Cycle. Much like the Atkinson cycle, Miller-Cycle uses variable valve timing to create a greater expansion stroke than compression stroke, but applied to turbocharged engines. The VW 2.0L EA888 Gen3B - DI turbocharged engine utilizes early intake valve closure, combined with higher boost turbocharging, to achieve acceptable performance while maintaining the efficiency benefits of Miller-Cycle. It is unreasonable to exclude this potential technology, since it is already in production. The omission will limit the effectiveness for turbocharged engines and cause adoption of more expensive solutions, thereby overstating the cost to achieve target CAFE fuel economy levels.

7. *Engine Maps - Gasoline Variable Geometry Turbocharger (VGT)*

A VGT enables better low-end torque and drivability without having to use a very small turbine, a compromise when using conventional turbocharger which increases backpressure and reduces efficiency over large positions of the engine map. VW introduced the EA211 TSI Evo engine in Europe in 2017, which is a 1.5-liter DI turbocharged Miller-Cycle gasoline engine with Variable Geometry Turbocharger (VGT). The 2018 PRIA does not include gasoline VGT engines which enable, among other advantages, cost-effective Miller-Cycle applications, which under predicts potential FE improvements.

8. Transmission Maps – Transmission Ratios

The 2018 PRIA analysis assumes that all transmissions with a given number of ratios (8-speed, 10-speed) maintain the same individual step ratios and shift maps, independent of the engine or hybrid-electric technology to which it is mated. This will result in powertrain inefficiencies and under-predict potential fuel economy benefits.

9. Transmission Maps – Shift Busyness

For some engine/vehicle combinations, the 2018 PRIA analysis calculates an extremely high number of transmission shifts (136 shifts) to occur during the US06 driving cycle. Such busyness would be completely unacceptable to passengers and over predicts the energy losses associated with such an extreme number of shifts.

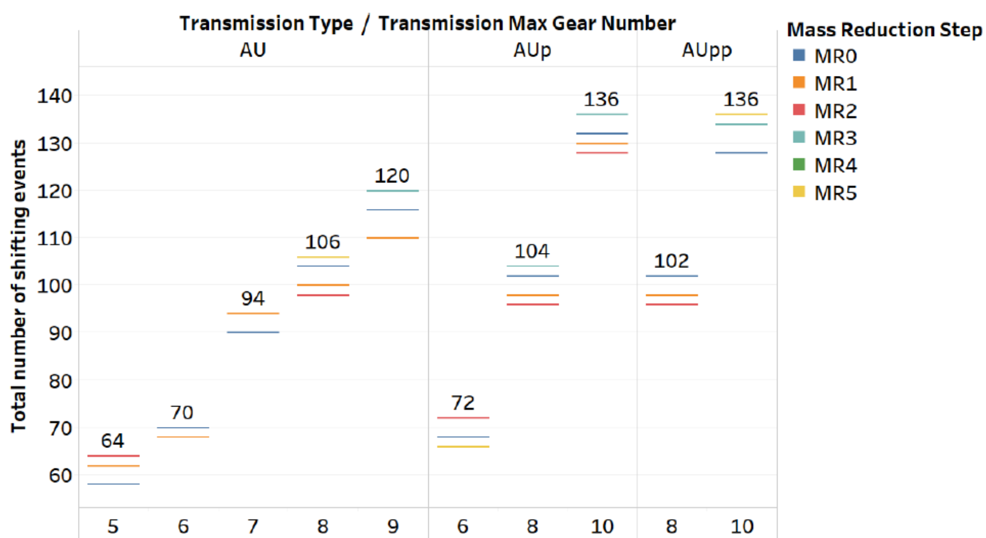

Figure 227: Total number of shifting events for AU/AUp/AUpp transmissions during US06 cycle

Figure 4: Shifting events

10. Electrification – Belt Integrated Starter Generator (BISG)

BISGs, which allow start-stop and supplemental torque, are gaining in market share. The introduction of 48-volt systems supports increased efficiencies in other vehicle systems, such as electrically-driven air conditioning compressors. The 2018 PRIA analysis of a BISG applied to full size pickup truck predicts a significantly-underpredicted FE improvement of 5.3%. For comparison, the FE benefit of a 48-volt BISG in the MY2018 Ram Pickup, showed 10% incremental improvement[11].

11. *Electrification – Crankshaft Integrated Starter Generator (CISG)*

CISGs are integrated into the block to mount the electric motor/generator. The CISGs allow more torque transfer than belt driven systems and expands the total system integration to include modifying engine operating parameters for synergistic efficiency improvements. The 2018 PRIA shown negligible improvement of CISG over BISG, which is significantly understated. Mitsubishi Electric is supplying the first production system to Mercedes-Benz[12], but current high costs and larger dimensions, compared to BISGs, will likely delay major market penetration until beyond the MY2025 time-horizon.

Other examples of inaccurate subsystem performance, which result in erroneous vehicle-level fuel economy improvement and inappropriate technology pathways to achieve fleet FE targets are included below.

12. The 2018 PRIA transmission modeling does not accurately capture the losses and FE penalty associated with a shift event.

13. The 2018 PRIA transmission modeling does not incorporate the concept of “Skip shifting” which is important for reducing shift busyness and increasing FE especially in vehicles equipped with transmission with a large number of ratios (8-10).

14. In the 2018 PRIA, as powertrain technology is added to individual vehicles, the final drive ratio is kept a constant. This ignores efficiency benefits due to down-speeding that are enabled by some of the powertrain technologies identified. Also, the transmission gear ratios are not optimized for a vehicle - powertrain combination which understates potential FE improvements.

15. Rolling resistance in the 2018 PRIA is erroneously assumed to be the same across different vehicle classes. Depending upon the vehicle size, power, acceleration and performance package, rolling resistance will vary.

16. There is a fuel economy penalty which occurs when the engine engages and disengages mechanically-derived cylinder deactivation. The 2018 PRIA does not consider this effect, which overstates the potential benefit. Proper consideration of these penalties would emphasize the very cost-effective skip-fire technology which was not included as a potential incremental technology. The net result will be an overestimation of cost to achieve a FE target.

[11] “First Drive: 2019 Ram 1500 eTorque Mild Hybrid,” Truck Trend, September 11, 2018, (http://www.trucktrend.com/features/1809-first-drive-2019-ram-1500-etorque-mild-hybrid)

[12] “Mitsubishi Electric Begins Mass-producing Auto Industry’s First Crankshaft ISG System for 48V Hybrid Vehicles,” Public Relations Division, Mitsubishi Electric Corporation, Press Release No. 3141, October 26, 2017

17. In addition to the discussion above, the 2018 PRIA additionally under predicts the efficiency improvement of employing a BISG. Taking advantage of the torque assist of the electric motor/generator, the engine can be further down-speeded, with a change to the final drive ratio and the transmission shift logic, which are excluded in the 2018 PRIA analysis. This causes further underprediction of potential FE incremental improvement.

2.2 Incremental Benefits

To accurately predict potential incremental improvements in FE, it is extremely important to understand the nature of the improvements being sought by each increment (improved thermodynamics, reduced friction, reduced vehicle weight, etc.). Without this understanding, the order, relative improvement, and cost-effectiveness of technology packages will vary significantly, thereby producing inappropriate results and erroneous conclusions.

As a first step, we reviewed the estimated improvements of discrete technology packages used in the 2018 PRIA and compared them to equivalent technologies which were presented in the 2016 Draft TAR associated with the midterm evaluation for model years 2022-2025. We then evaluated the reasonableness of the values based upon other peer-reviewed publications and our 40-year experience in automotive product design and development.

The results of our initial assessment suggest that there are seemingly wide variations in estimated incremental benefits associated with individual technology packages between the 2016 Draft TAR and 2018 PRIA. Furthermore, even the bases for evaluation can vary significantly and inappropriate product improvement pathways result.

Examples:

1. *Comparison of 2018 PRIA Turbocharged Engine Maps to State-of-the-art Engines*

   A principle reason for the understatement of incremental fuel economy improvement in the 2018 PRIA is the overly-conservative estimate of the underlying combustion engine efficiencies. Many production engines available today use the same technology packages as those identified in the 2018 PRIA. However, these state-of-the-art production engines demonstrate significantly higher efficiencies.

   Base Turbocharged engine (Turbo1)

   Figures 5, 6 and 7 allow a comparison of the brake-specific fuel consumption (BSFC) of the baseline turbocharged engine (PRIA_eng12) used in the 2018 PRIA analysis to the Honda L15B7 1.5L engine available in the 2016 Honda Civic. The units of measure are grams of fuel consumed per kilowatt hour (g/kWh) of engine output; therefore, lower is better

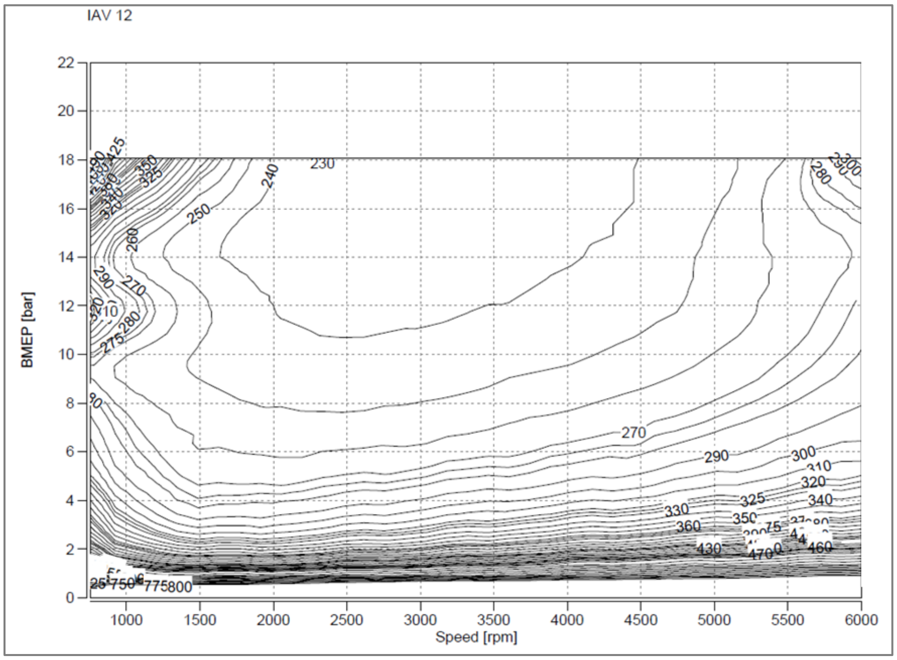

Figure 5: BSFC Map of PRIA_Eng12. 1.6L 4-cylinder base turbocharged engine (Source 2018 PRIA)

The PRIA_Eng12 turbocharged engine shown in Figure 5 is modeled with continuously variable valve lift (CVVL) on the intake side. This technology is relatively expensive[13] (>$300.00 over VVT in MY2017) but is intended to improve fuel consumption by reducing the thermodynamic losses due to pumping work while operating at low power levels.

Figure 6 shows a similar BSFC map for the Honda L15B7 turbocharged engine[14] that has continuously variable intake and exhaust camshaft phasing (CVVT) which is less expensive than CVVL. Figure 7 shows the mathematical difference between the maps.

[13] "Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles," National Research Council, The National Academy of Sciences Press, 2015

[14] EPA Vehicle and Fuel Emissions Testing Database (https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps)

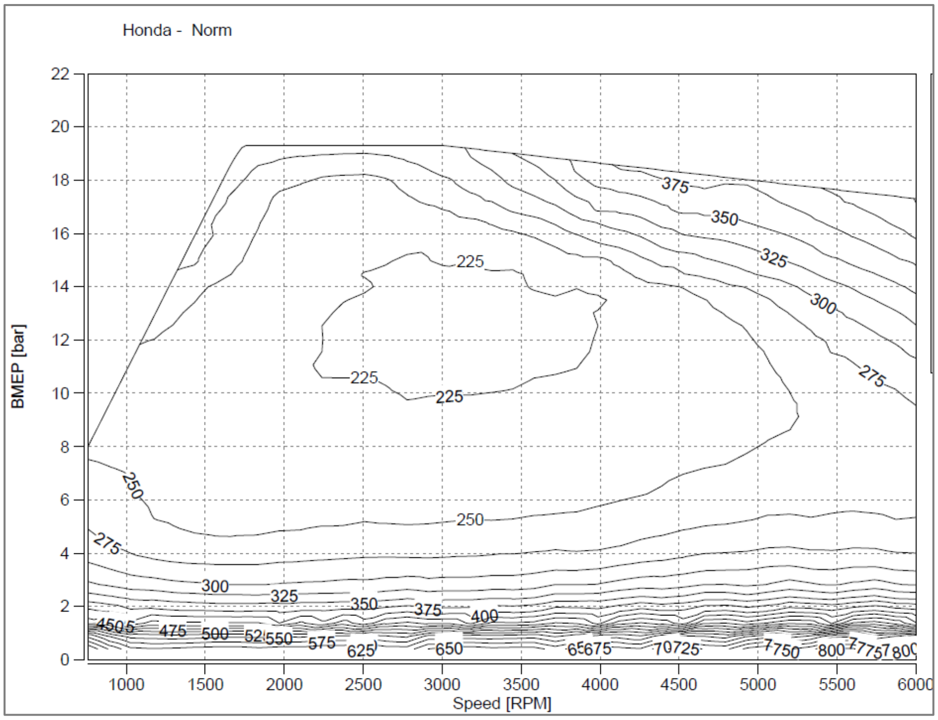

Figure 6: BSFC map of the Honda 1.5L L15B7 Engine used in the 2016 Honda Civic

Comparison of these fuel consumption maps shows that the Honda engine is almost 10% more efficient over a significant portion of the map that is most relevant to fuel economy test cycles. Also, since the L15B7 is the first generation of the new Honda turbocharged engine, even further fuel consumption improvement is highly likely in the period through MY2025.

Review of contour shapes in Figure 5 shows that the PRIA_Eng12 is predicted to have its highest efficiency at very high load and high engine speeds (up to 5,500 rpm). The engine map shows no degradation in BSFC at engine speeds between 2,000 rpm and 4,500 rpm, all the way up to peak load (18bar brake mean effective pressure: BMEP).

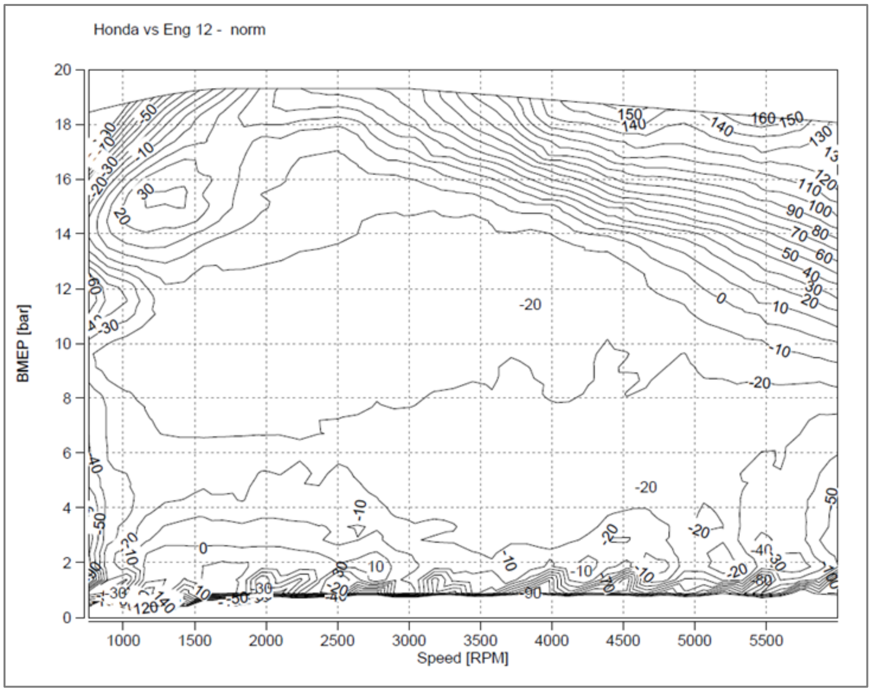

Figure 7: Delta (Honda 1.5L L15B7 – PRIA_Eng12)

This behavior is unrealistic because turbocharged engines at high loads require retarded spark timing to prevent knocking and fuel enrichment to prevent overheating of turbocharger and related components. These factors will increase fuel consumption and reduce efficiency under real-world conditions.

Another effect of this unrealistic fuel consumption curve would be to predict unreasonably good fuel consumption at very high power levels for downsized turbocharged engines. This could bias technology pathways in over-predicting fuel economy benefits for small engines installed in heavier engines. The predicted performance of the vehicle (drivability, acceleration, fuel consumption, etc.) would be overly optimistic, creating unrealistic real-world pathways.

2. *Comparison of 2018 PRIA Turbocharged Engine with Cooled EGR to Mazda SkyActiv*

Another engine technology pathway is the application of cooled exhaust gas recirculation (CEGR1) to turbocharged engines which improves fuel economy by helping to improve knock resistance, which reduces the necessary level of retarding spark timing to avoid knocking. This allows the compression ratio of the engine to be increased somewhat, which further improves thermal efficiency.

However, since these are turbocharged engines, which exacerbates knocking tendency, the increase in compression ratio is less than so-called HCR1 (high compression ratio, naturally-aspirated, direct injection engine) and HCR2 (HCR1 + cooled EGR) engines that begin to approach diesel-like efficiencies.

Figure 8 shows the BSFC map of the PRIA_Eng13 which is a 1.2L, I4 turbocharged, VVT, DI engine with cooled EGR. For comparison, Figure 9 shows the BSFC map for the Mazda 2.5L SkyActiv Turbo engine[15] which is available in the MY2016 Mazda CX-9 which also employs cooled EGR. Figure 10 shows the mathematical difference between the two BSFC maps, with all three figures using measurement units of grams of fuel consumed per kilowatt hour (g/kWh) engine output.

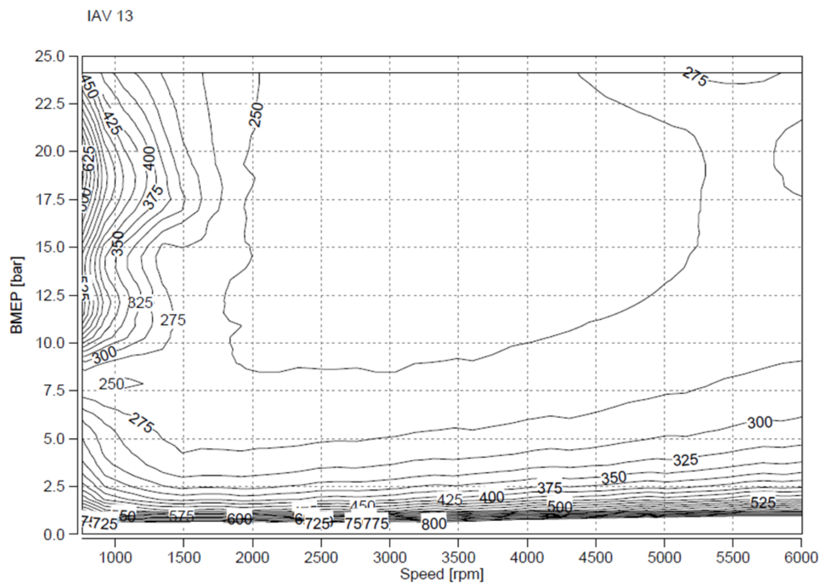

Figure 8: BSFC Map of PRIA_Eng 13: 1.2L I4 Turbo DI with Cooled EGR (Source 2018 PRIA)

Review of the figures shows that the BSFC of the Mazda turbo engine is about 20 g/kwh (about 10%) less than the PRIA_Eng13 engine over a significant portion of the test-cycle-relevant engine operating range (low and medium speed and loads). This would likely result in a fuel economy improvement of at least 10%, especially after proper mating of transmission gear ratios.

This is the first generation of the Mazda engine and it is likely that with further optimization and refinement of the combustion system, plus continued advancement in high energy ignition systems, the efficiency gains through cooled EGR will further improve

As was the case with PRIA_Eng12, the PRIA_Eng13 turbocharged engine with cooled EGR shows unrealistically high efficiency (unreasonably low BSFC) at the highest load (23bar BMEP) over a broad speed range from 2,000 rpm to over 5,000 rpm. At these very high loads, there is still the need to retard spark timing for knock control and perhaps a greater need for enrichment based upon the very high load level (>23bar).

[15] EPA Vehicle and Fuel Emissions Testing Database (https://www.epa.gov/vehicle-and-fuel-emissions-testing/combining-data-complete-engine-alpha-maps)

Therefore, a realistic engine will exhibit minimum fuel consumption “islands”, such as is shown Figure 9 for the Mazda SkyActiv engine.

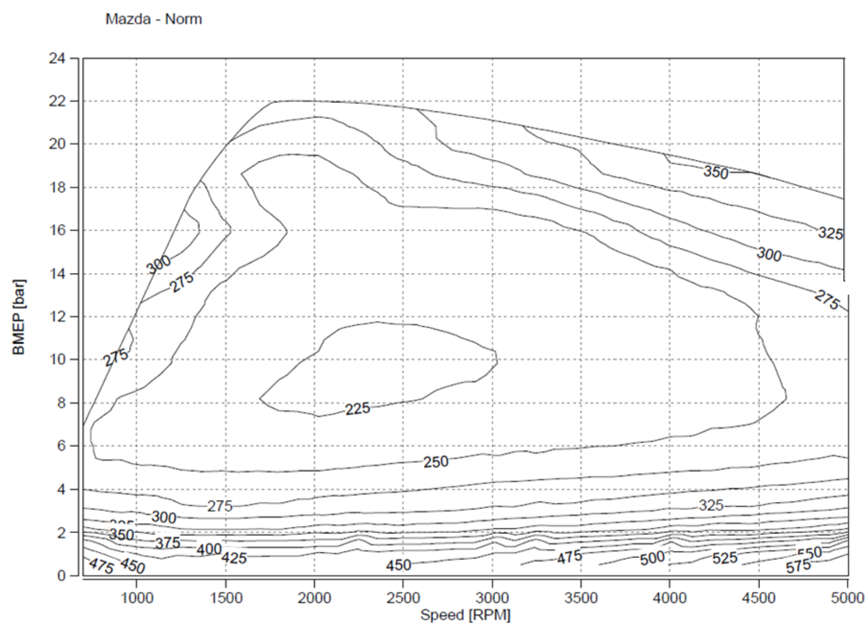

Figure 9: BSFC map of 2016 Mazda SKYACTIV-G Turbo 2.5L I4

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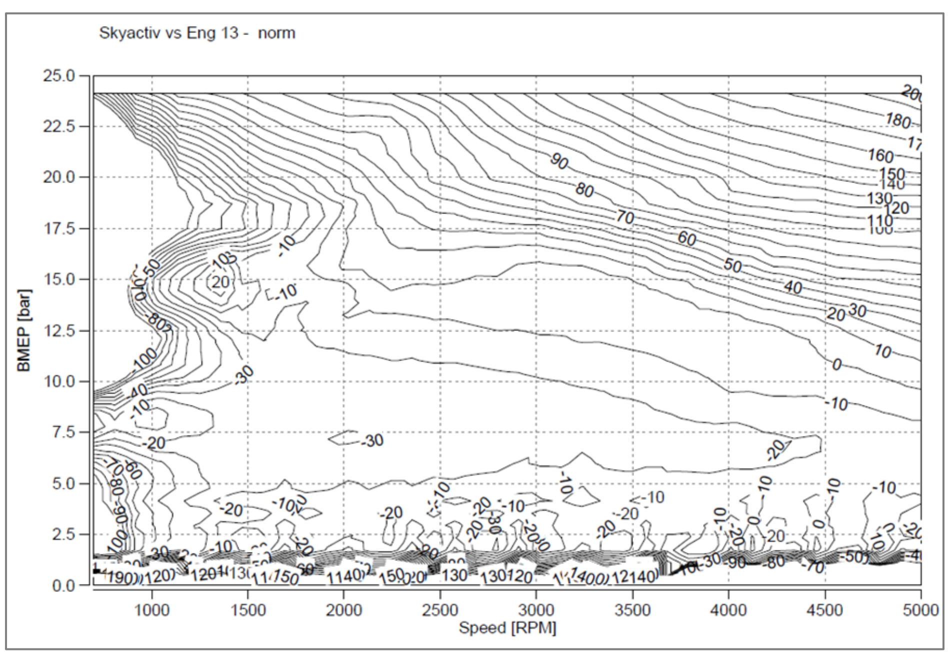


Figure 10: BSFC Delta (2016 Mazda SKYACTIV-G Turbo 2.5L I4 and PRIA_Eng13)

2.3 Technology Costs

As a first step in the assessment of incremental subsystem costs and effectiveness, Roush compared the estimated costs for technology paths between the 2018 PRIA and the 2016 TAR. Many significant differences between the cost assumptions were identified are summarized below.

The Table 3 shows values from 2016 Draft TAR (EPA) and 2018 PRIA (NHTSA) cost analysis for two engine technology packages. Since the 2018 PRIA and 2016 Draft TAR based their analysis on different year dollar (2013 for EPA, 2016 for NHTSA), the EPA costs were adjusted to 2016 dollars, assuming a cumulative 3% rate of inflation.

It is clear, from the comparison results, that the costs for the first technology package (VVT added to base engine) are very similar equivalent between the two analyses. However, there is a notable difference when looking at the results for the second engine technology package. The

Engine Tech Package	Notes	Engine / Cost Type [1]	$2016 (NHTSA) [2]					$2013 (EPA) [3]					$2013 (EPA) inflation adjusted to $2016 [4]				
			base year	2017	2021	2025	2029	base year	2017	2021	2025	2029	base year	2017	2021	2025	2029
DOHC + VVT	* VVT added to base NA DOHC engine * NHTSA modeled eng01 (table 6-5, pg. 22) * Assuming EPA's Dual Cam Phasing equals VVT	I4 / DMC [5,6]	$ 78.38	-	-	-	-	$ 74.00	$ 71.00	$ 66.00	$ 63.00	-	$ 76.22	$ 73.13	$ 67.98	$ 64.89	-
		I4 / TC [6,7]	-	$ 111.97	$ 108.79	$ 106.24	$ 104.13	-	$ 100.00	$ 87.00	$ 84.00	-		$ 103.00	$ 89.61	$ 86.52	-
		V6 / DMC [5,6]	$ 156.75	-	-	-	-	$ 160.00	$ 153.00	$ 142.00	$ 135.00	-	$ 164.80	$ 157.59	$ 146.26	$ 139.05	-
		V6 / TC [6,8]	-	$ 223.94	$ 217.58	$ 212.48	$ 208.25	-	$ 214.00	$ 188.00	$ 180.00	-		$ 220.42	$ 193.64	$ 185.40	-
		V8 / DMC [5,6]	$ 156.75	-	-	-	-	$ 160.00	$ 153.00	$ 142.00	$ 135.00	-	$ 164.80	$ 157.59	$ 146.26	$ 139.05	-
		V8 / TC [6,9]	-	$ 223.94	$ 217.58	$ 212.48	$ 208.25	-	$ 214.00	$ 188.00	$ 180.00	-		$ 220.42	$ 193.64	$ 185.40	-
DOHC + VVT + GDI + HCR	* VVT, GDI, HCR (Atkinson) added to base NA DOHC engine * NHTSA modeled eng24 (current SkyActiv) (table 6-5 pg. 22) * Assuming EPA's Dual Cam Phasing equals NHTSA's VVT, Atkinson 2 equals HCR1	I4 / DMC [5,10]	$ 1,021.93	-	-	-	-	$ 399.00	$ 389.00	$ 364.00	$ 344.00	-	$ 410.97	$ 400.67	$ 374.92	$ 354.32	-
		I4 / TC [5,7]	-	$ 1,297.66	$ 1,238.28	$ 1,216.88	$ 1,204.31	-	$ 543.00	$ 487.00	$ 458.00	-		$ 559.29	$ 501.61	$ 471.74	-
		V6 / DMC [5,11]	$ 1,636.66	-	-	-	-	$ 648.00	$ 632.00	$ 590.00	$ 558.00	-	$ 667.44	$ 650.96	$ 607.70	$ 574.74	-
		V6 / TC [8,11]	-	$ 2,088.22	$ 1,994.21	$ 1,959.22	$ 1,938.17	-	$ 882.00	$ 790.00	$ 742.00	-		$ 908.46	$ 813.70	$ 764.26	-
		V8 / DMC [5,12]	$ 2,051.53	-	-	-	-	$ 798.00	$ 789.00	$ 737.00	$ 695.00	-	$ 821.94	$ 812.67	$ 759.11	$ 715.85	-
		V8 / TC [9,12]	-	$ 2,604.33	$ 2,485.04	$ 2,442.15	$ 2,416.99	-	$ 1,097.00	$ 987.00	$ 922.00	-		$ 1,129.91	$ 1,016.61	$ 949.66	-

Table 3: Technology cost comparison – 2018 PRIA vs EPA

2018 PRIA costs are in the range of 2.3 to 2.5 times higher than the 2016 Draft TAR estimated costs. Since the VVT technology costs were almost identical, the difference must result from the predicted cost of Atkinson-cycle-related (HCR1) technologies.

These are just two examples of engine technology cost comparison. There are many other cases where cost varies significantly between the 2016 Draft TAR and the 2018 PRIA.

<u>Other Examples:</u>

1. *Engine Subsystem – Turbocharger*

   2018 PRIA costs are generally up to 2 times that of 2016 Draft TAR costs for turbocharger systems (Turbo 1 /2). The costs from the 2018 PRIA are over estimated while those of the 2016 Draft TAR are under predicted, assuming the total system is taken into consideration. Detailed analyses are required to determine which, if either, are more accurate, including defining all subsystem components including intercoolers, ducting, heat insulating materials, etc.

2. *Engine Subsystem – High Compression Ratio*

   The 2018 PRIA costs for implementing higher compression ratio (excluding variable compression ratio) are 5x-6x that the 2016 Draft TAR estimated costs. These costs are extremely high for implementing HCR technologies and will significantly overstate the incremental cost and bias technology pathways.

3. *Engine Subsystem – Cylinder Deactivation*

   The 2018 PRIA incremental costs to incorporate cylinder deactivation (excluding skip-fire control) appear low for implementing cylinder deactivation technologies, compared to 2016 Draft TAR and 2015 NAS. Furthermore, the incremental costs remain unchanged between different engine configurations which will bias technology pathways toward mechanical solutions which may better be implemented with other cost-effective control methodologies, such as dynamic skip-firing.

4. *Transmission – 8-Speed Dual Clutch Transmission (DCT)*

   Eight-speed DCTs (DCT8) are currently in production (MY2018), with quantities increasing significantly. However, the 2018 PRIA predicts incremental costs which are a factor of 1.4 higher than the 2016 Draft TAR estimated. Roush believes that the learning factors for such systems are significantly better than those estimated by either the 2018 PRIA or the 2016 Draft TAR.

3.0 Independent Analysis of Augural Standard-Compliance Pathways

To demonstrate the results of applying logical technology pathways to achieve compliance with augural standards, two (2) representative vehicle classes were chosen for vehicle performance and fuel economy prediction. Based upon the predicted market shift toward SUVs and other light-duty trucks, and due to the time constraints of the NPRM comment period, Roush limited its focus to a small SUV and a full-size Pickup as examples for predictive analysis.

Although the CAFE requirements for light-duty trucks are somewhat less stringent than for passenger cars, their aerodynamic constraints, weight requirements, trailer towing needs and associated higher horsepower requirements make them very instructive analytical test cases. This is especially true, considering market-driven purchase forces, their predicted growth in market share and therefore their contribution to the U.S. light-duty transportation CO_2 inventory.

Roush developed state-of-the-art engine maps based on production engines, which were adapted using the automotive industry-accepted GT-Power simulation code. We then developed transmission maps to maximize FE using industry-accepted optimization strategies within the GT-Drive vehicle simulation code, while maintaining constant vehicle performance. GT-Power was also used by contractors to Argonne National Laboratory (ANL) to generate input to their Autonomie vehicle simulation model, which in turn, served as input for the CAFE modeling performed by the Agencies and presented in the 2018 PRIA. We then developed transmission maps and utilized industry-accepted optimization strategies within the GT-Drive vehicle simulation code to calculate vehicle performance and fuel economy parameters.

3.1 Small SUV Compliance with MY2025 Augural Standards

Due to the popularity and growth of the small SUV segment, Roush conducted engine, transmission, performance calibration and fuel economy analyses to determine a logical technology pathway and associated cost to comply with the augural 2025 CAFE standards. To begin the analysis, the 2018 Mazda CX-5 small SUV was chosen as a representative vehicle against which our vehicle model could be calibrated. Also, due to the inclusion of a high compression ratio, Atkinson-cycle engine in its SkyActiv powertrain, we considered this a good example of technology progression in the midsize SUV segment.

Next, we chose a similar small SUV, the Toyota Rav4 as a baseline vehicle, using input parameters, and followed the 2018 PRIA-stated logic for MY2016 baselines. We then developed a logical technology pathway and followed industry-accepted full vehicle system calibration and FE optimization at constant vehicle performance to determine the incremental FE improvements necessary for CAFE compliance. The MY2025 augural target fuel economy for this vehicle, based upon its footprint, is 58.0 mpg, combined city-highway.

Table 4 summarizes the incremental technology pathway developed by Roush as a logical progression through cost-effective technologies for a small SUV-class vehicle, in this case a Toyota Rav4. In developing this scenario, Roush employed the GT Suite of engine map, transmission maps, traditional calibration strategies to optimize fuel consumption under constant performance, and the application of incremental costs which Roush considered reasonable and supported by the 2016 TAR, 2015 NAS, Tier-1 supplier publications and Roush's experience in powertrain and vehicle design for manufacturing.

MY	Org.	Vehicle	Class	Engine	MPG	Technologies	Costs
2016	PRIA	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	32.85	DOHC; VVT; AT6; CONV; ROLL0; MR1; AERO0	$0.00
2016	Roush	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	32.85	DOHC; VVT; AT6; CONV; ROLL0; MR1; AERO0	$0.00
2020	PRIA	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	32.85	DOHC; VVT; AT6; ROLL0; MR1; AERO0	$0.00
2020	Roush	Toyota Rav4 AWD	Small SUV	2.0L I4 (NA)	42.02	HCR1: AT6; CONV; ROLL20, MR1; AERO10, 48V-BISG	$1,659.37
2023	PRIA	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	32.85	DOHC; VVT; AT6; ROLL0; MR1; AERO0	$0.00
2023	Roush	Toyota Rav4 AWD	Small SUV	1.9L I4 (NA)	56.61	HCR2; AT8; ROLL20, MR3; AERO10, 48V-BISG	$1,842.42
2024	PRIA	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	58.00	HCR1; AT8; SHEVP2; ROLL20; MR4; AERO20	$4,553.12
2024	Roush	Toyota Rav4 AWD	Small SUV	1.9L I4 (NA)	56.61	HCR2; AT8; ROLL20, MR3; AERO10, 48V-BISG	$1,795.97
2025	PRIA	Toyota Rav4 AWD	Small SUV	2.5L I4 (NA)	58.00	HCR1; AT8; SHEVP2; ROLL20; MR4; AERO20	$4,422.26
2025	Roush	Toyota Rav4 AWD	Small SUV	1.8L I4 (NA)	57.92	HCR2; AT8; ROLL20, MR4; AERO10, 48V-BISG	$1,767.06

Table 4: Technology Pathway Comparison between Roush and 2018 PRIA CAFE Model for Small SUV

The results from the analysis are further presented in Figure 11 where the incremental fuel economy improvement is plotted versus vehicle model year, for both the 2018 PRIA results and the Roush results for a Toyota RAV4 AWD. Also shown is the target CAFE fuel economy by model year based upon the footprint of the RAV4.

Figure 12 presents the accumulated cost by model year to achieve the fuel economy values summarized in Table 4 and presented in Figure 11. Again, the 2018 PRIA projection for the RAV4 is compared to the Roush analysis.

The results show that the use of proper engine and transmission maps, which are optimized depending upon the engine characteristics, combined with engine displacement and gear ratio optimization as vehicle weight is reduced, predict that compliance with augural 2025 standards can be achieved without the application of P2 hybridization, which was chosen by the 2018 PRIA CAFE model

The pathway of engine technology choice replicates applications currently applied in the Mazda CX-5 (HCR1) plus a 48V BISG, such as that applied in the MY2019 Jeep Wrangler with 2.0L turbo engine. The evolution to HCR2 with cooled EGR, such as the Toyota Dynamic Force Engines (but is not available in the CAFE model), together with some minor downsizing of the engine, combined with a BISG, properly optimized to support engine transients, produces a very cost-effective package.

The purpose of this analysis is to show that proper design optimization of engine and transmission subsystems, combined with reasonable estimates for incremental improvement, especially with the BISG, results in a predicted cost which is 60% less than that of the CAFE model.

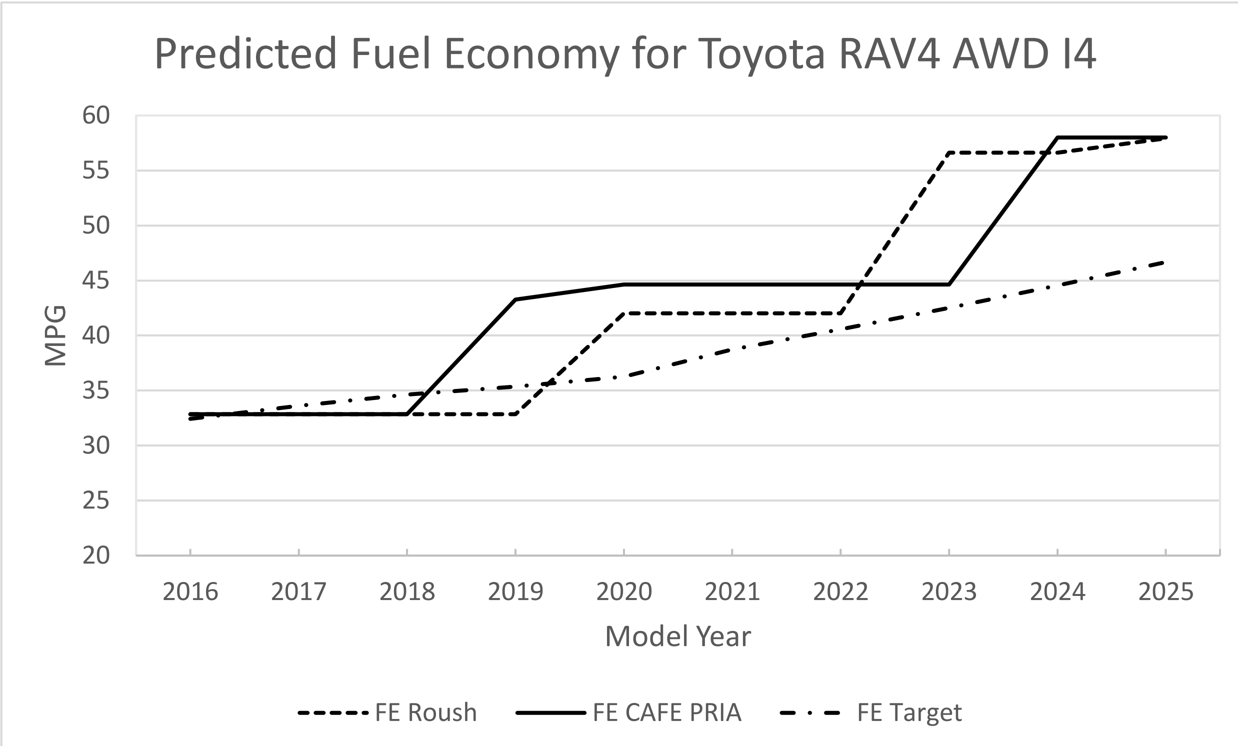


Figure 11: Predicted Fuel Economy for Toyota RAV4 AWD I4

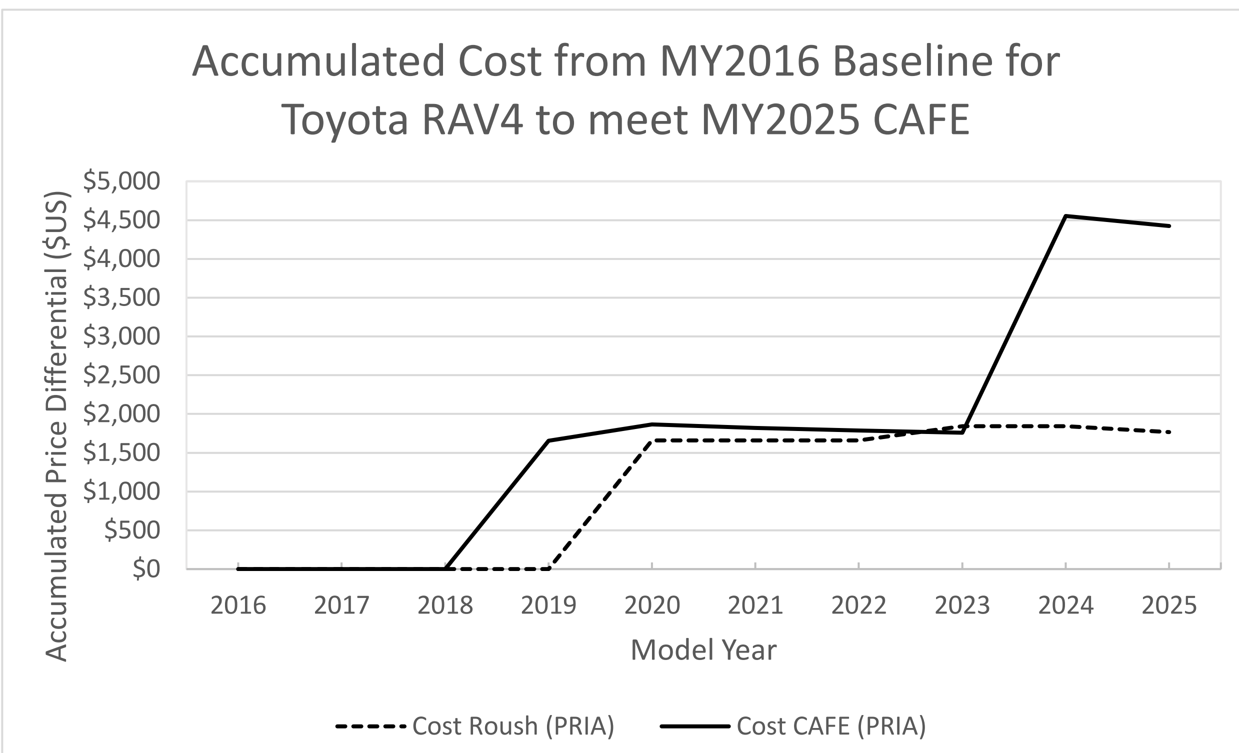


Figure 12: Accumulated Cost to Comply with MY2025 CAFE for Toyota RAV4 AWD I4

3.2 Full-Size Pickup Compliance with MY2025 Augural Standards

Full-size pickup trucks also represent a relatively large portion of the U.S. light-duty vehicle market and due to their absolute level of fuel economy and CO_2 emissions, they contribute significantly to the greenhouse gas inventory. In a similar fashion to the small SUV analytical procedure, we chose a Ram pickup with a 66 sq. ft. footprint and 3.6L V6 NA engine as our baseline vehicle against which to calibrate our engine and vehicle models.

Based upon the high cost-effectiveness related to high compression ratio and BISG mild hybridization, as shown in the small SUV case, we proceeded to apply a BISG, HCR1, HCR2 and cylinder deactivation engine strategy, combined with transmission ratio and shift strategy optimization. We also evaluated the potential for weight reduction and some level of aerodynamic and rolling resistance improvement, while maintaining constant vehicle performance.

It is important to note that all the technology steps chosen are currently in production in various platforms across different manufacturers. Therefore, their inclusion in our exemplar pathway represents a very viable product evolution cycle.

Table 5 summarizes the incremental technology pathway developed by Roush as a logical progression through cost-effective technologies for a full-size pickup, in this case a Ram with a 3.6L V6 naturally-aspirated engine. As in the small SUV case, Roush adapted published, production engine maps with GT-Power and utilized GT-Drive together with transmission maps, optimized gear ratios, traditional shift strategies and calibration algorithms to optimize fuel consumption under constant performance. We also applied incremental costs which Roush considered reasonable and are supported by the 2016 Draft TAR, 2015 NAS, and Roush's experience in powertrain and vehicle design for manufacturing.

The results from the analysis are further presented in Figure 13 where the incremental fuel economy improvement is plotted versus vehicle model year, for both the 2018 PRIA results and the Roush results for the Ram 1500 4x2 V6, together with the target CAFE FE model year. Figure 14 presents the associated accumulated cost by model year to achieve the FE values summarized in Table 5 and presented in Figure 13.

The results show that the use of proper engine and transmission maps, which are optimized depending upon the engine characteristics, combined with engine displacement and gear ratio optimization as vehicle weight is reduced, predict that compliance with augural 2025 standards can be achieved very cost-effectively, without the expense of highly-boosted, down-sized turbocharged engines.

The pathway of engine technology choice replicates applications currently applied in the Mazda CX-5 (HCR1) plus a 48V BISG, which has been introduced in a Ram pickup and Jeep Wrangler for MY2019. The evolution to HCR2 with cooled EGR, such as the Toyota Dynamic Force Engines, combined with a BISG, properly optimized to support engine transients, produces a very cost-effective package.

As was the case with the small SUV example, this analysis shows that proper design optimization of engine and transmission subsystems, combined with reasonable estimates for incremental improvement which are supported by published test data, results in a very cost-effective method to comply with the MY2025 augural standards. As can be seen from Table 5, Roush has chosen a naturally aspirated pathway with cylinder deactivation, direct injection, and increased compression ratio, combined with a 48V BISG. Production-reasonable engine and transmission maps were combined with optimized transmission gear ratios and shift schedules.

MY	Org.	Vehicle	Class	Engine	MPG	Technologies	Costs
2016	PRIA	Ram 1500 4x2	Full-Size Pickup	3.6L V6 (NA)	25.6	DOHC; VVT; AT8; CONV; ROLL20; MR0; AERO5	$0.00
2016	Roush	Ram 1500 4x2	Full-Size Pickup	3.6L V6 (NA)	25.2	DOHC; VVT; AT8; CONV; ROLL20; MR0; AERO5	$0.00
2019	PRIA	Ram 1500 4x2	Full-Size Pickup	Turbo CEGR1 V6	35.8	CEGR1; AT10; BISG; ROLL20; MR3; AERO15	$4,110.89
2019	Roush	Ram 1500 4x2	Full-Size Pickup	3.6L PFI V6 DEAC	28.4	DOHC; DEAC; AT8; ROLL20, MR3; AERO15; BISG	$1,770.92
2022	PRIA	Ram 1500 4x2	Full-Size Pickup	Turbo CEGR1 V6	35.8	CEGR1; AT10; BISG; ROLL20; MR4; AERO15	$3,687.22
2022	Roush	Ram 1500 4x2	Full-Size Pickup	3.6L PFI HCR1 V6	32.8	HCR1; AT8; BISG; ROLL20, MR3; AERO15	$2,192.41
2025	PRIA	Ram 1500 4x2	Full-Size Pickup	Turbo CEGR1 V6	35.8	CEGR1; AT10; BISG; ROLL20; MR3; AERO15	$3,371.87
2025	Roush	Ram 1500 4x2	Full-Size Pickup	3.6L PFI HCR2 V6	38.2	HCR2+DEAC; AT8; BISG; ROLL20; MR4; AERO15	$2,359.52

Table 5: Technology Pathway Comparison between Roush and 2018 PRIA CAFE Model for Full-Size Pickup

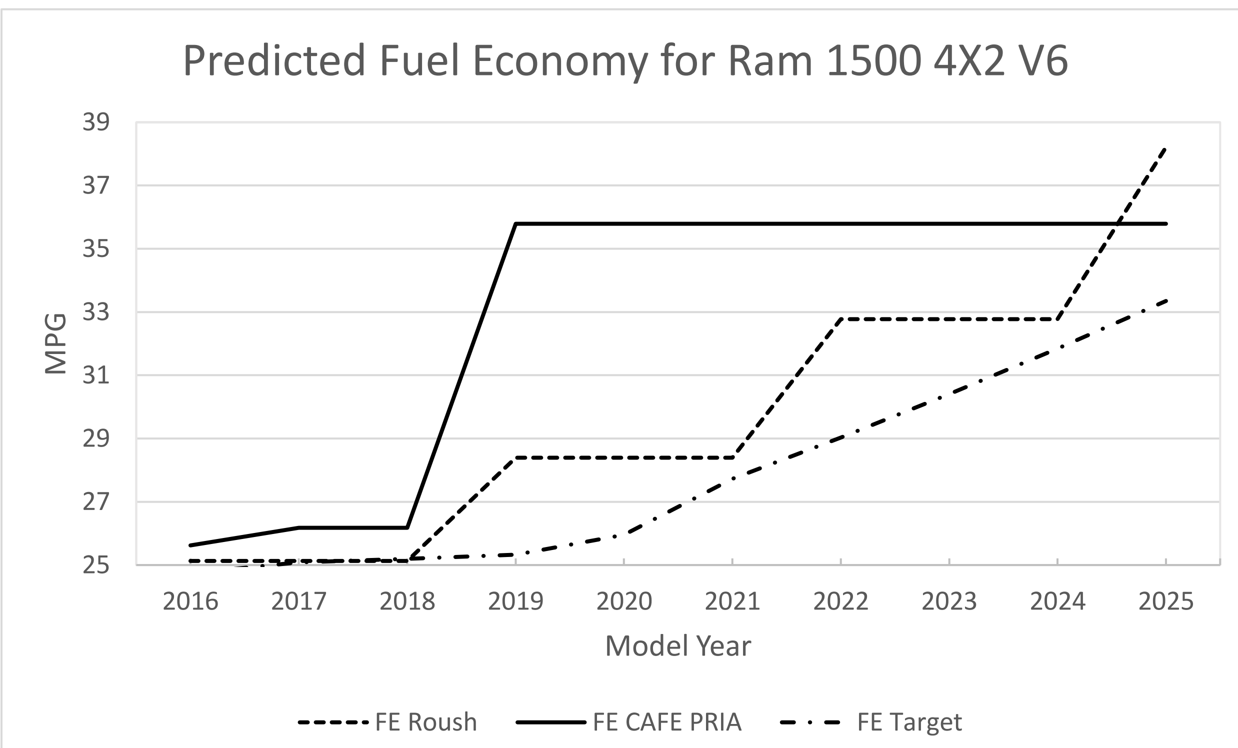


Figure 13: Predicted Fuel Economy for Ram 1500 4x2 V6

The 2018 PRIA CAFE model predicts compliance with the MY2025 augural standard of 33.3 mpg, by achieving 35.8 mpg, at a predicted cost of $3,371.87 in 2025. This technology pathway follows downsized turbocharging with cooled EGR and a 48V BISG.

However, a much more cost-effective path is possible as shown by the Roush-proposed naturally-aspirated, high compression ratio engine, also combined with a BISG, but modelling accurate incremental effectiveness and reasonable incremental cost.

The Roush proposal is shown to achieve an even greater fuel economy level, at 38.2 mpg by MY2025, and exceed the augural standards each year from MY2016 to MY2025. This is accomplished at an incremental cost of $2,359.52 in MY2025, which is over $1,000.00 less expensive, or a projected cost reduction of over 30%.

This analysis further exemplifies the compounding issues associated with inaccurate engine and transmission shift maps, lack of retuning transmission and differential gear ratios as engine parameters change, the use of accurate effectiveness levels, improper CAFE Model constraints and overstated incremental costs.

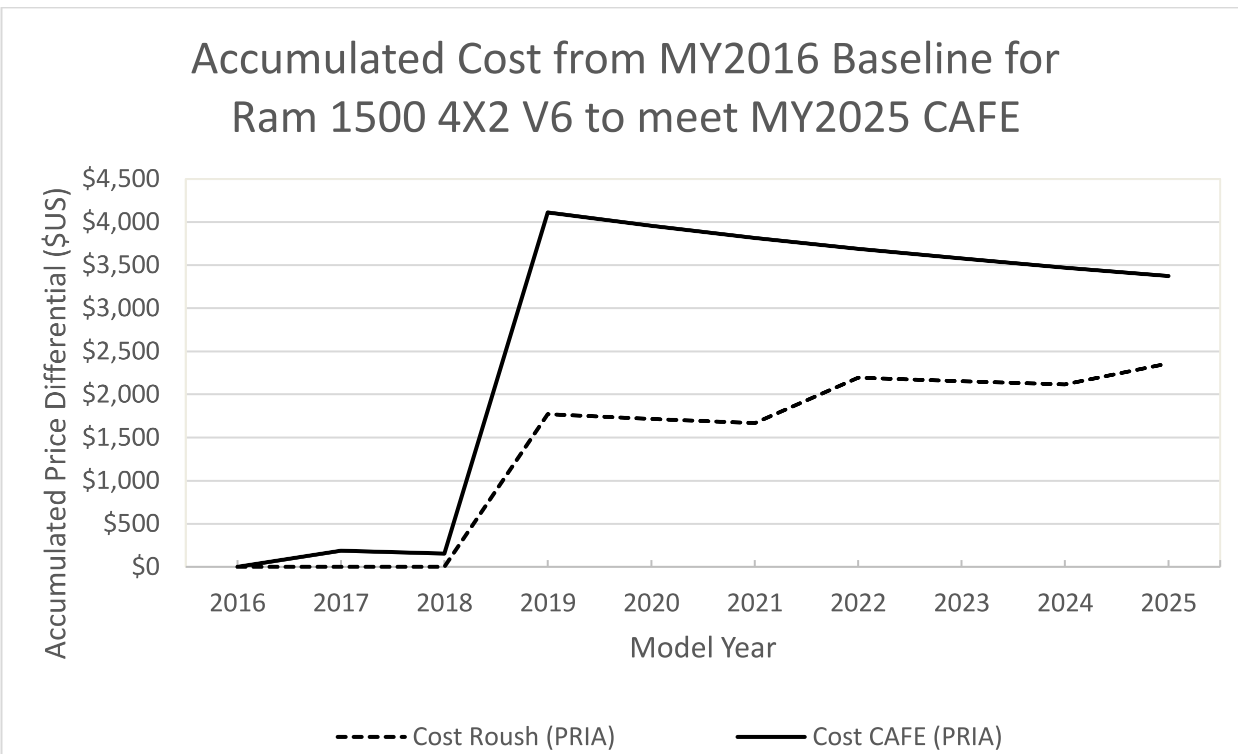


Figure 14: Accumulated Cost to meet MY2025 CAFE for Ram 1500 4x2 V6

4.0 Conclusions

Roush has shown that the use of logical, unrestricted technology pathways, with incremental benefits supported by industry-accepted vehicle simulation and dynamic system optimization and calibration, together with publicly-defensible costs, allows cost-effective solutions to achieve target fuel economy levels which meet MY2025 existing standards.

It is also important to note that all the technology steps chosen to achieve MY2025 target CAFE fuel economy levels for our two test cases (Small SUV and Full-Size Pickup) are currently in production within various platforms across different manufacturers.   Therefore, their inclusion in our exemplar pathways represents a very viable product evolution cycle

Of primary importance is establishing accurate engine maps, transmission maps, fuel economy optimizing shift strategies, reestablishing transmission gear ratios and shift points as powertrain and vehicle characteristics change (such as addition of mild hybrid system) and defining technology pathway algorithms that are consistent with normal product development constraints. Since we are, in most cases, considering small, incremental improvements in efficiency, accurate engineering analyses are critical in determining technical viability to achieve future fuel economy targets.

The development of reasonable cost estimates is also important to understand the probability of commercial success for future technology approaches. However, variability in worldwide manufacturing and financial markets, the impact of foreign regulatory climates on new technology cadence (such as vehicle electrification in China) and other variables make accurate prediction of component- or system-level costs very challenging. Furthermore, continued advancements in traditional technology, combined with supplier willingness to reduce margin with increasing competition, will also influence future technology pricing.

We have not performed a complete fleet-compliance simulation. However, we have identified many areas for improvement which, if enacted, would likely produce significantly different results in the overall fleet CAFE compliance assessment.

Appendix 1: GT-Power Analysis of Small SUV

Fuel Economy GT Model Calibration Results – Mazda CX5

Vehicle Specs							
Sim Tool	MY	Manuf	Model	Platform	Engine	Drive	Transm
CAFE	2016	Mazda	CX-5	Skyactiv	2.0L I4 (NA)	FWD	MT6
GT	2014	Mazda	CX-5	Skyactiv	2.0L I4 (NA)	FWD	MT6

GT FE Model Calibration to CAFE (Uses HCR1 and CX-5 specs)											
Overall Information					Key Simulation Inputs						
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	Trsm Shft Schd	Eng CR	Tire RR Coeff	Veh Mass (lbm)	Diff Ratio	Coeff Drag (Cd)	Front Area (m^2)
2016	Augural	CAFE	baseline	HCR1; MT6; CONV; ROLL0; MR3; AERO5	Autonom AT6	13:1	0.009	3212.0	4.624	0.36	2.65
2016	Augural	GT	baseline		Autonom AT6	13:1	0.009	3212.0	4.624	0.36	2.65
2016	Augural	GT	baseline		GT OptAT6	13:1	0.009	3212.0	4.624	0.33	3.07

GT FE Model Calibration to CAFE (Uses HCR1 and CX-5 specs)											
Overall Information					Simulation Output: MPG				EPA Unadj MPG est		
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	HWFET	UDDS	Combined	Comb Delta	HWFET	UDDS	Combined
2016	Augural Cafe Stds	CAFE	baseline	HCR1; MT6; CONV; ROLL0; MR3; AERO5	?	?	39.20	0%	48.90	33.70	39.18
2016	Augural Cafe Stds	GT	baseline		47.86	33.58	38.79	-1.07%			
2016	Augural Cafe Stds	GT	baseline		49.91	33.41	39.24	0.11%			

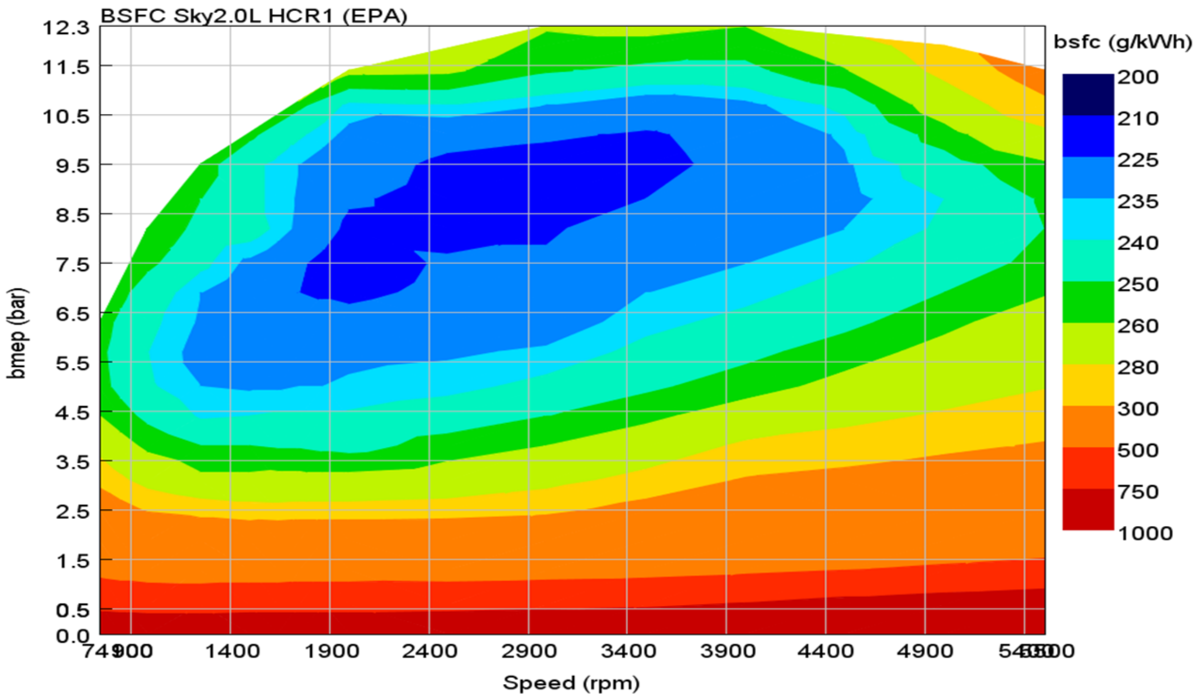
Fuel Economy Analysis Results – Toyota RAV4

Vehicle Specs							
Sim Tool	MY	Manuf	Model	Platform	Engine	Drive	Transm
GT	2020 to 2025	Toyota	RAV4	Skyactiv HCR1, HCR2 and Optimized AT6, AT8	2.0L, 1.8L, 1.8L I4 (NA)	AWD	AT6, AT8

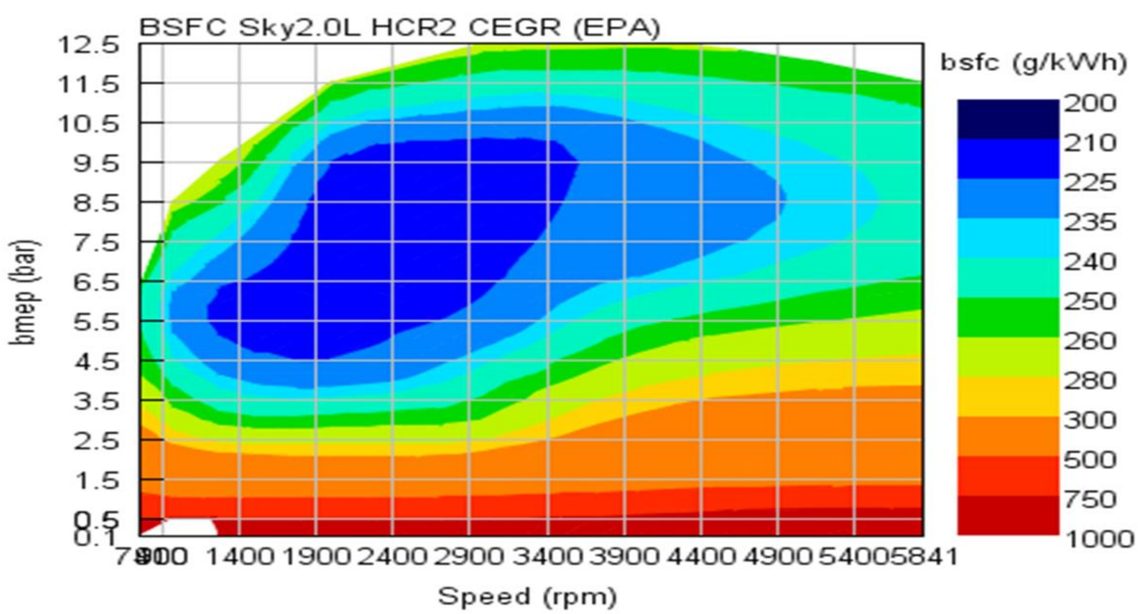
FE Benefit from Technology Walk (Simulated in GT Power)											
Overall Information					Key Simulation Inputs						
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	Trsm Shft Schd	Eng CR	Tire RR Coeff	Veh Mass (lbm)	Diff Ratio Opt	Coeff Drag (Cd)	Front Area (m^2)
2016	Augural	CAFE	baseline	DOHC; VVT; AT6; CONV; ROLL0; MR1; AERO0	Autonom AT6	10.4:1	0.009	3570	?	0.36	2.65
2020	Augural	GT	v.2020	HCR1; AT6; CONV; ROLL20; MR1; AERO10; 48VBISG	GT OptAT6	13:1	0.0072	3570.0	4.5	0.324	2.65
2023	Augural	GT	v.2023	HCR2; AT8; CONV; ROLL20; MR3; AERO10; 48VBISG	GT OptAT8	14:1	0.0072	3480.8	4.0	0.324	2.65
2025	Augural	GT	v.2025	HCR2; AT8; CONV; ROLL20; MR4; AERO10; 48VBISG	GT OptAT8	14:1	0.0072	3382.1	4.0	0.324	2.65

FE Benefit from Technology Walk (Simulated in GT Power)									
Overall Information					Simulation Output: MPG				
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	HWFET	UDDS	Combined	Comb BISG 10%	Comb Delta
2016	Augural	CAFE	baseline	DOHC; VVT; AT6; CONV; ROLL0; MR1; AERO0	?	?	32.85	na	0%
2020	Augural	GT	v.2020	HCR1; AT6; CONV; ROLL20; MR1; AERO10; 48VBISG	51.30	31.60	38.20	42.02	14%
2023	Augural	GT	v.2023	HCR2; AT8; CONV; ROLL20; MR3; AERO10; 48VBISG	59.24	46.48	51.47	56.61	36%
2025	Augural	GT	v.2025	HCR2; AT8; CONV; ROLL20; MR4; AERO10; 48VBISG	60.30	47.70	52.65	57.92	38%

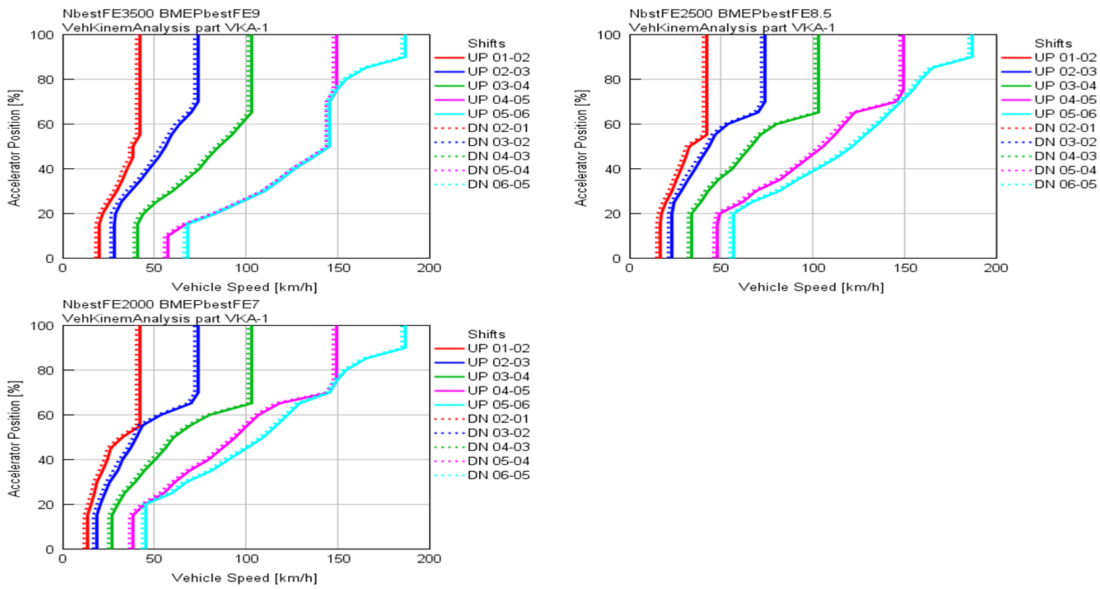
BSFC Map used in GT Analysis – Skyactiv 2L HCR1



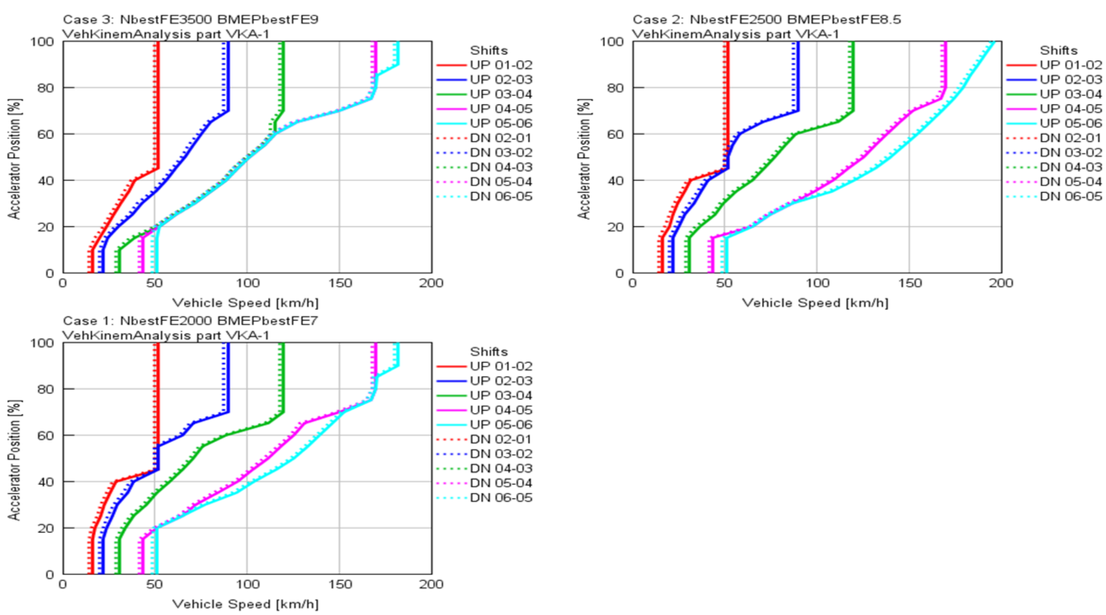
BSFC Map used in GT Analysis – Skyactiv 2L HCR2



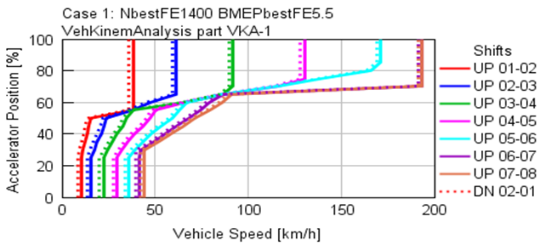
Optimized shift Schedules – Skyactiv 2L with AT6 – CX5

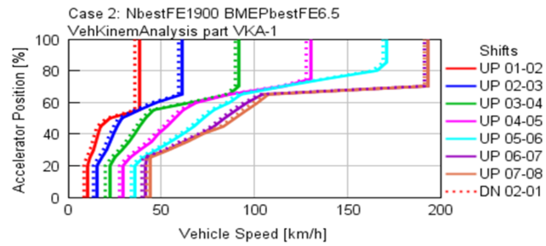


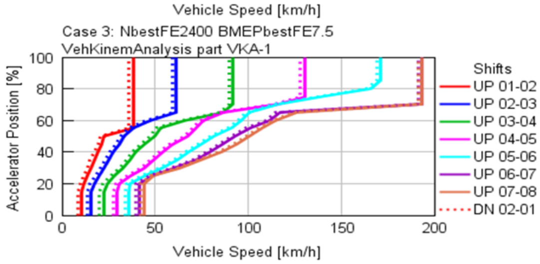
Optimized shift Schedules – Skyactiv 2L with AT6 – RAV4

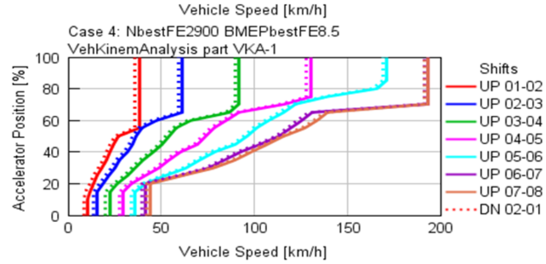


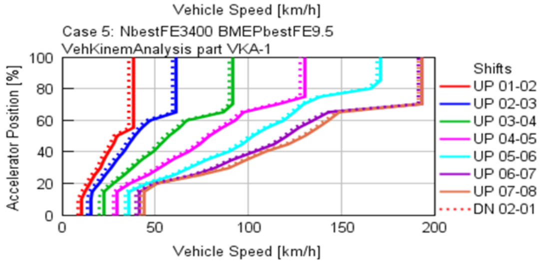
Optimized shift Schedules – Skyactiv 2L with AT8 – RAV4











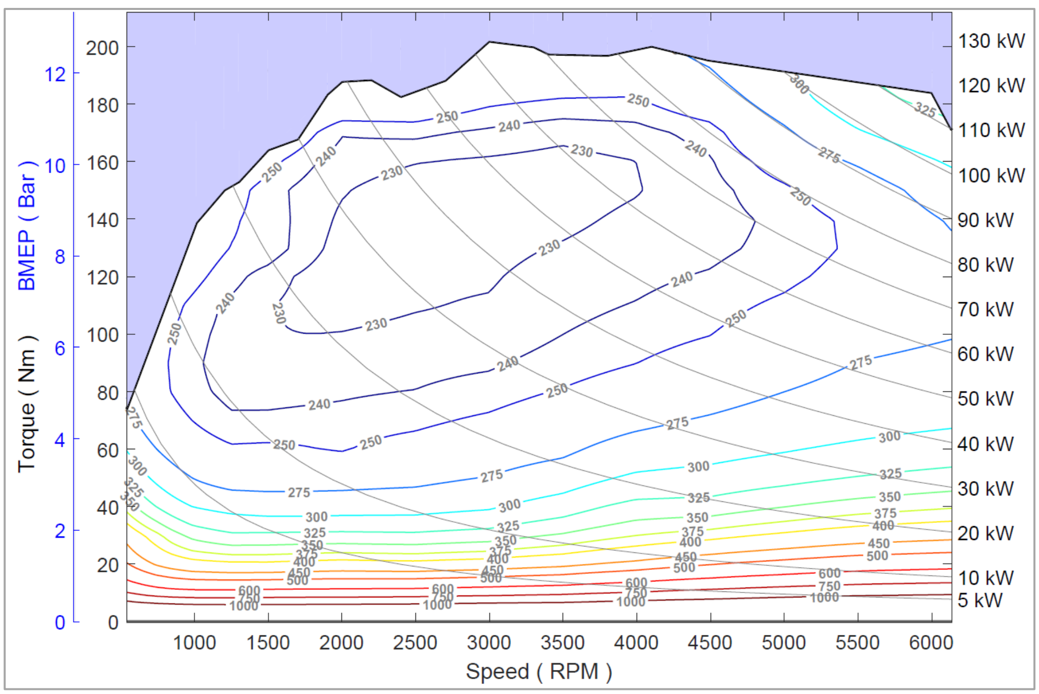
Appendix 2: GT-Power Analysis of Full-Size Pickup

Fuel Economy simulation results of the pickup truck

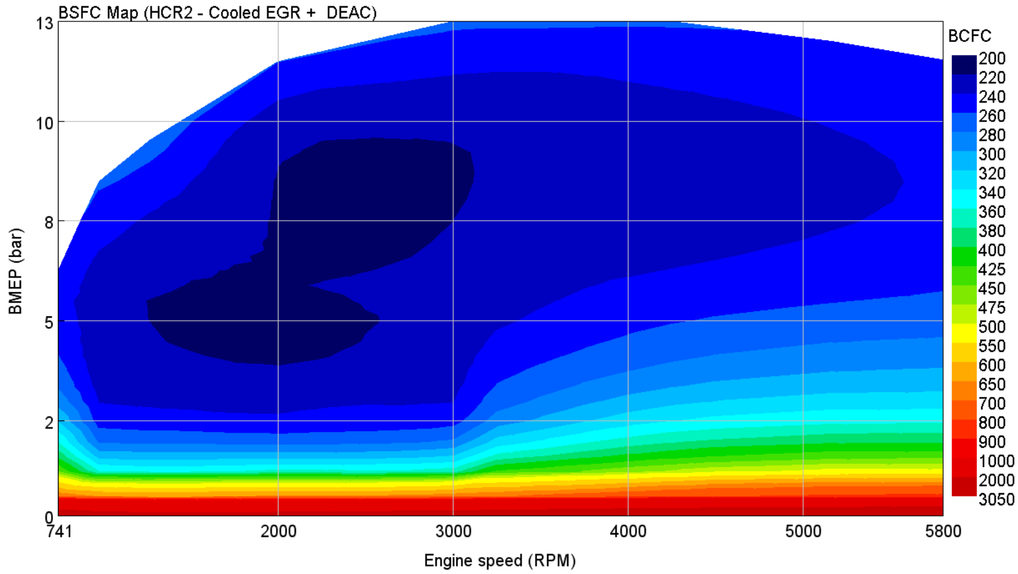
FE Benefit from Technology Walk (Simulated in GT Power)											
Overall Information					Key Simulation Inputs						
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	Trsm Shft Schd	Eng CR	Tire RR Coeff	Veh Mass (lbm)	Diff Ratio Opt	Coeff Drag (Cd)	Front Area (m^2)
2016	Augural	GT	baseline	DOHC; VVT; AT8; CONV; ROLL20; MR0; AERO5	Autonom AT8	10.4:1	0.0072	4750	3.98	0.399	3.25
2019	Augural	GT	v.2016	DOHC; DEAC; VVT; AT8; BISG; ROLL20; MR3; AERO15	GT OptAT8	10.4:1	0.0072	4500	3.70	0.324	3.25
2022	Augural	GT	v.2019	HCR1; AT8; BISG; ROLL20; MR3; AERO15	GT OptAT8	13:1	0.0072	4500	3.70	0.324	3.25
2025	Augural	GT	v.2022	HCR2+DEAC; AT8; BISG; ROLL20; MR4; AERO15	GT OptAT8	14:1	0.0072	4275	3.52	0.324	3.25

FE Benefit from Technology Walk (Simulated in GT Power)					
Overall Information					Simulation Output: MPG
MY	Scenario 0	Sim Tool	Platf Version	Tech Pack	
2016	Augural	GT	baseline	DOHC; VVT; AT8; CONV; ROLL20; MR0; AERO5	25.13
2019	Augural	GT	v.2016	DOHC; DEAC; VVT; AT8; BISG; ROLL20; MR3; AERO15	28.39
2022	Augural	GT	v.2019	HCR1; AT8; BISG; ROLL20; MR3; AERO15	32.78
2025	Augural	GT	v.2022	HCR2+DEAC; AT8; BISG; ROLL20; MR4; AERO15	38.21

BSFC maps used for the Pickup truck fuel economy simulation

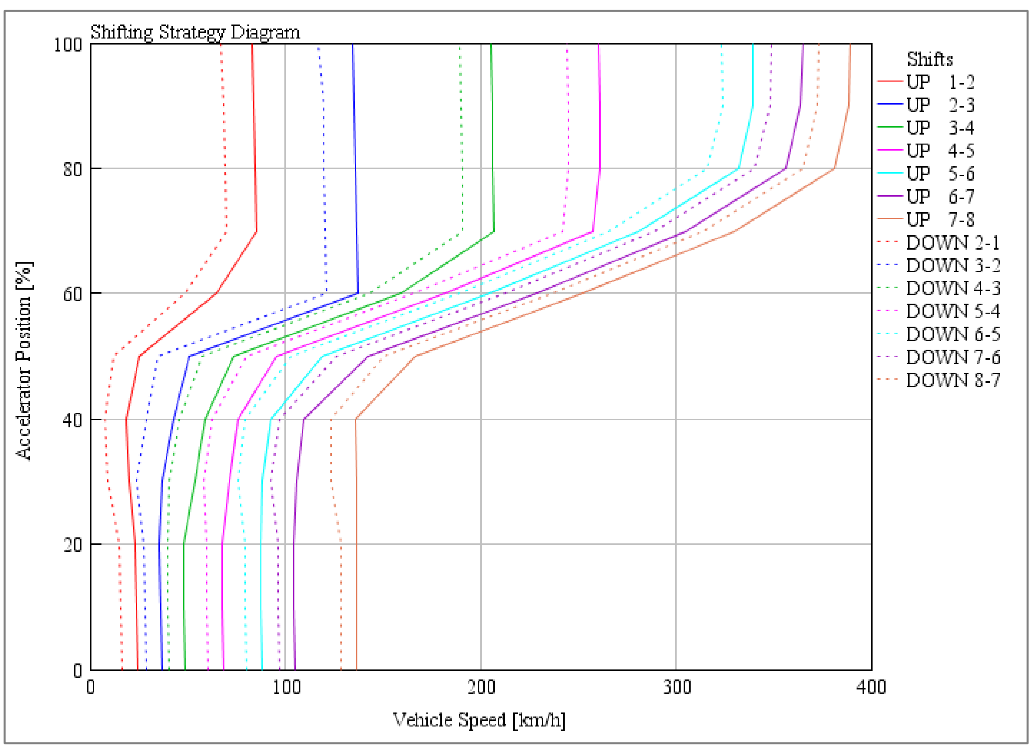


HCR1 Engine map



HCR2 + Cylinder Deactivation Engine map

Shift Schedule used for pickup truck fuel economy simulation



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