Estimating GHG Reduction from Combinations of Current Best-Available and Future Powertrain and Vehicle Technologies for a Midsized Car Using EPA's ALPHA Model

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John Kargul, Andrew Moskalik, Daniel Barba, Kevin Newman, and Paul Dekraker

US Environmental Protection Agency

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Abstract

The Environmental Protection Agency's (EPA's) Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created to estimate greenhouse gas (GHG) emissions from light-duty vehicles[1]. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of all internal energy flows in the model. The software tool is a MATLAB/Simulink based desktop application. In preparation for the midterm evaluation of the light-duty GHG emission standards for model years 2022-2025, EPA is refining and revalidating ALPHA using newly acquired data from model year 2013-2015 engines and vehicles. From its database of engine and vehicle benchmarking data EPA identified the most efficient, engines, transmissions and vehicle technologies, and then used ALPHA to model a midsized car incorporating combinations of these existing technologies which minimize GHG emissions. In a similar analysis, ALPHA was used to estimate the GHG emissions from future low-GHG technology packages potentially available in model year 2025. This paper presents the ALPHA model inputs, results and the lessons learned during this modeling and assessment activity.

1.0. Introduction

Background

During the development of the Light-Duty Greenhouse Gas (GHG) and Corporate Average Fuel Economy (CAFE) standards for the years 2017-2025, EPA utilized a 2011 light-duty vehicle simulation study [2] from the global engineering consulting firm, Ricardo, Inc. The previous study provided EPA with several rounds of full-scale vehicle simulations to predict the effectiveness of future advanced low-GHG technologies. Use of data from this study is documented in the August 2012 EPA and NHTSA *Joint Technical Support Document* [3] which was utilized during the Federal Rule Making for the 2017-2025 Light-Duty GHG Emission Standards and CAFE Standards.

The LD GHG rule required that a comprehensive advanced technology review, known as the mid-term evaluation, include an updated assessment of the cost and the effectiveness of advanced technologies available to manufacturers to meet the emission standards for model years 2022 to 2025. EPA has enhanced its Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) model [1] to improve the simulation of current and future vehicles, and as a tool for understanding vehicle behavior, fuel economy, GHG emissions and the effectiveness of various powertrain technologies. The National Academies of Science (NAS) reports recommend that these types of simulations are the best way for EPA to estimate the effectiveness of combinations of technologies [19]. To estimate GHGs, ALPHA calculates CO_2 emissions based on test fuel properties and fuel consumption for a vehicle technology package. No other emissions are calculated at the present time, but future work on other emissions is not precluded.

ALPHA will be used to confirm and update, where necessary, technology efficiency data from the previous Ricardo study such as the latest efficiencies of advanced downsized turbo and naturally aspirated engines. It may also be used to understand effectiveness contributions from advanced technologies not considered during the original Federal rulemaking, such as continuously variable transmissions (CVTs) and Atkinson cycle engines in non-hybrid applications.

The work behind this paper was performed by EPA's National Center for Advanced Technology (NCAT), located at its National Vehicle and Fuel Emissions Laboratory in Ann Arbor, Michigan, shown in Figure 1. While part of a federal laboratory, NCAT has been a global leader in development and demonstration of low-greenhouse gas emitting, highly fuel efficient hybrid drivetrain technologies, and is currently researching future advanced engine and transmission technologies to support modeling, advanced testing, and demonstrations of low GHG technologies.

Figure 1. EPA's National Vehicle and Fuel Emissions laboratory located in Ann Arbor, Michigan

NCAT engineers have further developed ALPHA as an in-house research tool to explore in detail current and future advanced vehicle technologies. ALPHA is being refined and updated to more accurately model light-duty vehicle behavior and to provide internal auditing of all energy flows within the model. To validate the performance of ALPHA, EPA has performed in-depth vehicle benchmarking and modeling projects involving several conventional and hybrid vehicles.

Focus

This paper presents EPA's initial analysis using of some of the key vehicle and engine benchmarking data that it has collected. Using the engine fuel maps, transmission maps, and operational control data acquired from benchmarking 2013, 2014, and 2015 vehicles, EPA has been able to create and study potential CO2 reduction benefits that come from creating various combinations of the best of these technologies in a midsized car.

EPA did this analysis as part of its process to prepare its ALPHA vehicle simulation model for its eventual use during the midterm evaluation for the 2022-2025 light-duty GHG standard. EPA's analysis of these modeling results provided a scientific quality control tool to help study a large amount of CO2 modeling results to find and correct any inconsistencies that could occur within the modeling process.

This analytical work is intended to provide the foundation for additional work on vehicle technology packages in the standard car class and for other sized vehicles. Future papers are planned to share the expanded results of other vehicle and engine benchmarking, validation and modeling currently underway at EPA.

While the estimates of GHG reduction potential presented in this paper show a promising potential for midsize cars to achieve the light-duty GHG standards for model years 2022 to 2025, it must be said that EPA has not used the initial data in this paper or its analysis to make any conclusions or decisions regarding the midterm evaluation for the light-duty GHG rule. EPA only desires to share information about its modeling approach and the progress it has made towards predicting GHG emissions from various technologies.

2.0. Overview of ALPHA's Approach to Modeling Vehicle GHG Emissions

EPA's ALPHA tool is a MATLAB/Simulink based desktop application which was created to estimate greenhouse gas (GHG) emissions from current and future light-duty vehicles. ALPHA is a physics-based, forward-looking, full vehicle computer simulation capable of analyzing various vehicle types with different powertrain technologies, showing realistic vehicle behavior, and auditing of all internal energy flows. There are several EPA SAE papers which describe the development and use of the ALPHA model [1] [4] [5] [6] [7] [8] [13] [15] [16] [17].

Vehicle and Engine Benchmarking for Validation of ALPHA Simulations

In preparation for the midterm evaluation of the light-duty GHG emission standards for model years 2022-2025, EPA is refining and revalidating ALPHA using newly acquired data from model year 2013-2015 engines and vehicles. During 2014 and 2015, EPA has been involved with testing over 25 different types of conventional and hybrid vehicles/engines across a wide range of powertrains and segments. A sample of the vehicles being tested is shown in Table 1. The vehicles/engines on the list were chosen based on our need to evaluate key technologies like naturally aspirated and boosted I4/I6/V6 engines, using 5, 6 and 8+ speed automatic and dual-clutch transmissions, as well as CVTs. The test vehicles included gasoline and diesel cars, SUVs and pickups. The vehicle list shown below is constantly evolving and growing. A sample list of the vehicles is shown here to give a sense of the scope of technology being evaluated in EPA's advanced automotive technology test program. Work is continuing to test even more vehicles and engines, building on this body of test data.

Data from chassis and engine dynamometer tests on these vehicles and engines were used to understand manufacturers' application of these advanced technologies, and to create engine fuel consumption and transmission efficiency maps for use in ALPHA's simulations. These data and engine maps were used to validate ALPHA's ability to correctly simulate vehicle operation, and to estimate fuel economy and CO2 emissions as compared to the actual laboratory chassis dynamometer tests of the vehicles.

Table 2 shows the driving cycles used during chassis dynamometer vehicle testing, and the corresponding cycles used by ALPHA to simulate vehicle operation. ALPHA assumes that the lab results it simulates are from a 2WD dynamometer.

Since ALPHA does not simulate a vehicle's cold-start operation, a cold temperature adjustment must be made to the CO2 estimate for the bag1 result of the simulated hot-start FTP. Bags 1, 2 and 3 of the FTP are each simulated separately under warm conditions. The multiplier is then only applied to the simulation result for bag1.

Table 1. Sample list of 2013/2014/2015 cars and trucks tested in preparation for its midterm evaluation of the LD GHG standards for 2022-2025 model years

Cars with Naturally Aspirated Gasoline Engines	Cars with Turbo Gasoline Engines	Cars with Diesel Engines
2009 Toyota Camry w/5AT	2013 Ford Escape 1.6L EcoBoost I4	
2013 Malibu 2.5L I4 w/6AT	2013 Ford Focus 1.6L EcoBoost I4 [Euro]	
2013 Mazda 6 Skyactiv 2.5L I4 w/8MT	2013 Sonata 2.0L I4 6AT	
2013 Mazda 3 Skyactiv 2.0L I4 13:1cr w/8MT	2015 Subaru Forester 2.0L I4	
2013 Mazda 3 SkyActiv 2.0L I4 13:1cr w/6AT	2015 Volvo S60 2.0L I4 Drive-E w/8AT	
2013 Mazda 3 SkyActiv 2.0L I4 14:1cr [Euro]	PSA 1.6L (engine only)	
2013 Altima SV 2.5L I4 Jatco CVT8	2016 Honda Civic 1.5L EarthDreams w/CVT	
2016 Acura ILX 2.4L I4 w/DCT plus torque converter		
Chrysler 300 3.6L V6 Pentastar w/8AT		2013 Mercedes E350 3.0L V6 w/7AT
Dodge Charger 3.6L V6 Pentastar w/5AT		
Dodge Charger 3.6L V6 Pentastar w/8AT		

Truck/SUVs with Naturally Aspirated Gasoline Engines	Truck/SUVs with Turbo Gasoline Engines	Truck/SUVs with Diesel Engines
2014 RAM HFE 3.6L V6 Pentastar w/8AT	2015 Aluminum F150 2.7L V6 EcoBoost	2014 RAM 1500 3.0L V6 EcoDiesel VM w/8AT
2014 Silverado 4.3L V6 w/ cylinder deactivation EcoTec3 w/6AT		BMW X5 35d 3.0L I6

Table 2. Driving cycles used in chassis dynamometer testing and in ALPHA simulations

Vehicle Chassis Dynamometer Tests	Order of Drive Cycles within the ALPHA Simulation	Comments
Actual cold-start FTP cycle	Simulated hot-start FTP cycle	EPA City 3-bag Federal Test Procedure cycle
HWFET prep cycle followed by HWFET test cycle	Simulated HWFET prep cycle followed by HWFET test cycle	Highway Fuel Economy Test cycle
US06 cycle	Simulated US06 cycle	High-speed cycle
(no comparable cycle for chassis tests)	Simulated vehicle performance cycle	Used to estimate performance neutrality

The adjustment factor varies with model year and represents a reasonable estimate for how much extra fuel is used to warm up a cold engine and transmission during the beginning of the FTP test cycle (bag 1). The adjustment factor applied by ALPHA gets smaller as manufacturers incorporate more advanced techniques to warm the engine and transmission faster such as using post-catalyst exhaust heat to warm up engine and transmission oils.

The adjustment factor values used in this study were the same ones used in the original Ricardo model used for the Federal Rulemaking for the light-duty GHG rule [2]. The Ricardo model assumed that 2008 vintage vehicles would have cold fuel consumption bag1 results that are 25% higher than those from a fully warm vehicle. Ricardo also assumed that this adjustment would be lowered to 11% for a more advanced 2020 vintage vehicle. We plan to study bag fuel consumption reported in certification data results [9] to assess Ricardo's assumptions and to understand the trends occurring with new model vehicles.

During ALPHA validations, the individual bag CO2 results from each chassis test are compared to the corresponding ALPHA CO2 simulated result. A weighted combination of city and highway cycle values (55% city and 45% highway) is also calculated and compared.

EPA sets +/- 5% as the minimum target for agreement between ALPHA validation results and chassis dynamometer test cycle data. Many of the validations show even tighter agreement such as those shown below:

- EPA's ALPHA validation of a 2013 GM Malibu showed that ALPHA agreed within +/- 1% of the chassis dynamometer tests [4].
- Validation of a 2013 Nissan Altima 2.5S with a CVT showed that ALPHA agreed within +/- 3.1% of the chassis dynamometer testing using UDDS and HWFET cycles [10].
- ALPHA validations of two 2014 Dodge Chargers, both with 3.6 liter V6 engines and either a NAG1 five-speed automatic transmission or an FCA845RE eight-speed automatic transmission, yielded combined cycle agreements of -0.2% for the 5-speed vehicle, and -1.3% for the 8-speed vehicle [7].
- A special validation was run to check how well ALPHA results would agree with those produced by the original Ricardo model used for the Federal Rulemaking for the light-duty GHG rule [2]. Using the same inputs as Ricardo model used, the ALPHA results agreed within +/-1%.

In addition to these validations, EPA is continuing to validate ALPHA using data from other vehicles shown in Table 1.

Using ALPHA to Predict Emissions of Future Technology Vehicles

After a specific modeling feature of ALPHA has been tuned and validated with data gathered from recent model year vehicles, it can begin to be utilized to estimate GHGs from different combinations of technologies in various vehicle packages. For example, the high compression ratio, normally aspirated Atkinson cycle engine, which is used in the 2014 Mazda 3 could be combined with a CVT such as that used in the Nissan Altima validation or with an advanced 8-speed automatic transmission. Another example would be to study the GHG reduction effects of a 10-20% reduction in vehicle weight coupled with engine start-stop technology for a particular vehicle type and engine/transmission combination.

3.0. Simulation Matrix Study of GHG Reduction Potential of Various Technology Combinations

Comprehensive modeling of various combinations of current and future vehicle technologies forms the data for a “matrix” of simulation results for a standard car (midsized passenger vehicle). For the remainder of the paper, this matrix will be known as the “standard car matrix”, or just the matrix.

The characteristics of the baseline “standard car” chosen for this matrix analysis were from the following standard car chassis:

- 2008-era Toyota Camry
- equivalent test weight (ETW): 3625 lbs
- Coastdown coefficients:
  A=29.81 lbs, B = 0.171 lbs/mph, C = 0.01864 lbs/mph^2
- Rolling resistance: Crr = 0.010
- Unadjusted certification fuel economy:
  26.7 mpg city, 42.5 mpg highway, 32.1 combined mpg
- combined CO2: 32.1 mpg combined = 283 g/mile

The standard car matrix analyzes 20 distinct technologies which are grouped into the following technology categories:

1. Three engines
2. Five transmissions
3. Four levels of weight reduction
4. Three levels of aerodynamic drag reduction
5. Three levels of rolling resistance reduction
6. Two levels of engine stop/start controls

Table 3 contains a brief description of each of the 20 technologies modeled. More details of these technologies is contained in the next section. A full factorial simulation, containing all combinations of the 20 technologies studied (representing 1080 unique vehicle technology packages), was run to determine the effects of each technology individually and in combination.

Table 3. Advanced technologies included in the simulation matrix

3 Engines: • **2008 Baseline -** Camry 2.4L I4 engine from the 2010 Ricardo analysis for LD GHG Federal Rulemaking (FRM) • **2014 Naturally Aspirated -** Mazda SkyActiv 2.0L I4 13:1 compression ratio engine • **Future TDS** – 24-bar down-sized turbo with cooled EGR from the 2010 Ricardo analysis for LD GHG Federal Rulemaking (FRM)
5 Transmissions: • **2008 AT5** – parameters from vehicle testing • **2013 AT6** – parameters from vehicle testing • **2014 AT8** – parameters from EPA trans stand testing • **2020 Future AT8**– constructed using paper published by ZF • **2020 Future DCT8** – constructed using damp DCT7 data provided by a supplier
4 reductions of Mass: • Base (0% reduction) • 5% reduction • 10% reduction • 15% reduction
3 reductions of Aerodynamic resistance (Cd): • Base (0% reduction) • 10% reduction • 20% reduction
3 reductions of Rolling Resistance (Crr): • Base (0% reduction) • 10% reduction • 20% reduction
2 modes of 12 volt Start-Stop technology: • Base (0% start-stop) • 100% start-stop

4.0. Key Modeling Factors and Considerations for the Standard Car Matrix Built into ALPHA

Since this paper is primarily focused on techniques to analyze and compare the GHG reduction potential of numerous powertrain and vehicle technologies, a complete description of ALPHA’s modeling methods and techniques is not included in this paper. However, it is useful to understand the basic descriptions of several key simulation factors that are programmed into ALPHA. These key modeling factors were established during the numerous ALPHA validations which used benchmarking test data from real 2013-2015 model year vehicles and engines.

Specific Modeling Factors and Considerations Associated with Vehicle Related Technologies

1. **Roadload Force -** ALPHA’s roadload force at a specific vehicle velocity (v) is determined by using the following formula:

$$F = Cv^2 + Bv + A \tag{1}$$

   where, the coastdown coefficients (A, B, and C) are derived from a least squares fit of data from track coast-down tests. These coefficients are available from the EPA certification test car data files [9].

   The coefficients correspond to:

   A. a factor for the roadload force that is mostly associated with tire rolling resistance as related to the vehicle mass

B. a small factor, which represents higher order rolling resistance and gearing loss factors beyond the rotating friction losses accounted for by the A coeffcient

C. a factor which mostly represents aerodynamic air drag

2. **% Reduction of Weight** - For the standard car matrix, the base vehicle's equivalent test weigh (ETW) is 3625 pounds. ALPHA's weight reduction parameter represents a straight percentage reduction in the (ETW), which ALPHA uses to adjust the A coefficient of the roadload force equation.

   *For example, ALPHA assumes the baseline standard car has a tire Crr factor of 0.010, and a base mass of 3571 pounds (3625/1.015), thus the baseline weight related rolling resistance force for the vehicle (0.01*3571) is replaced from the base A coefficent and an updated force representing the percentage of mass reduction is added back in.*

   Note that ALPHA uses 1.015 as its correction factor when simulating 2WD dynamometer testing where only one of the vehicle's two axles is rotating.

3. **% Reduction of Rolling Resistance** - For the standard car matrix, the baseline tire Crr factor is 0.010. ALPHA's rolling resistance reduction parameter represents a straight percentage reduction in the (Crr), which ALPHA uses to adjust the A coefficient of the roadload force equation.

   *Similar to the example for point 2 above, ALPHA assumes the baseline standard car has a tire Crr factor of 0.010, and a base mass of 3571 pounds (3625/1.015), thus the baseline weight related rolling resistance force for the vehicle (0.01*3571) is replaced from the base A coefficent and an updated force representing the percentage of Crr reduction is added back in.*

4. **% Reduction of Aerodynamic Resistance** - The roadload C coefficient is assumed to entirely represent aerodynamic losses, so a 10% aero improvement results in a 10% reduction in the C coefficient.

Specific Factors and Considerations for Transmission Technologies

1. **Transmission drive efficiency, gear ratios and spread** - this data was provided for each transmission in this analysis from the following sources:
   a. ***AT5*** - 5-speed transmission based on Charger AT5 gear ratios with losses comparable to GM6T40 (AT6) transmission
   b. ***AT6*** - 6-speed transmission based on data from FEV benchmarking of the GM6T40 (AT6) [4]
   c. ***AT8*** - 8-speed transmission based on data from FEV's benchmarking of the FCA845RE 8AT in the 2015 Charger (real-wheel drive large car) [7], scaled down to match torque output of Camry, efficiency reduced by 2% to account for adding a FWD differential
   d. ***Future AT8*** - an update to the FCA845RE AT8 data based on information from ZF's SAE paper about futuring an AT8 [11]
   e. ***Future DCT8*** - constructed using supplier-provided DCT7 data and expanded to 8-speed using ZF gear ratios [7]

2. **Final drive efficiency and ratio** - For the standard car analysis, the vehicle is assumed to be a Toyota Camry with a final drive ratio of 3.23. A final drive efficiency of 100% is used because differential losses are lumped in with the transmission.

3. **Transmission resizing** - The only transmission that was resized was the AT8 based on benchmark data from the FCA845RE in the 2015 Charger. The torque losses in the version of this transmission used in this study were scaled to simulate a transmission with lower torque throughput suitable for an I3 or I4 engine.

4. **Transmission shift strategy** - The **"**ALPHAshift" strategy was used to control shifting for all runs in the matrix, with the same standard set of shift parameters for all the runs in the matrix that use each transmission [5].

5. **Torque converter** - EPA used data from two real torque converters; the one used in the GM6T40 (AT6); and the one used in the FCA845RE (AT8). The AT6 transmissions uses the GM6T40 torque converter data. The AT8 transmission uses the FCA845RE torque converter data. All the TC's have their K-factor curve adjusted on a per engine basis to set the stall speed at 2500 rpm.

6. **Torque converter lockup** - lockup strategy for each transmission is based on the minimum lockup gear discovered during dynamometer testing of vehicles with these transmissions or literature pertaining to future transmissions. Generally, the more advanced transmissions lock up in a progressively lower gear and spend more time actually locked during the cycles. More information about ALPHA's and industry's torque converter lockup strategies can be found in the following references: 6-speed transmissions [4], 5-speed and 8-speed transmissions [7], and future transmissions [11] [12].

Specific Factors and Considerations for Engine Technologies used for the Standard Car Matrix

1. **Engine maps** - The following four engine maps were used to derive the steady-state fuel efficiency maps used in the simulations for the standard car matrix:
   a. ***Baseline engine*** - A 2008-era Camry engine. The map was generated from Ricardo data & images from EPA's LD GHG rulemaking [3]. The map in Figure 2 assumes the use of Tier2 certification fuel (AKI 93).

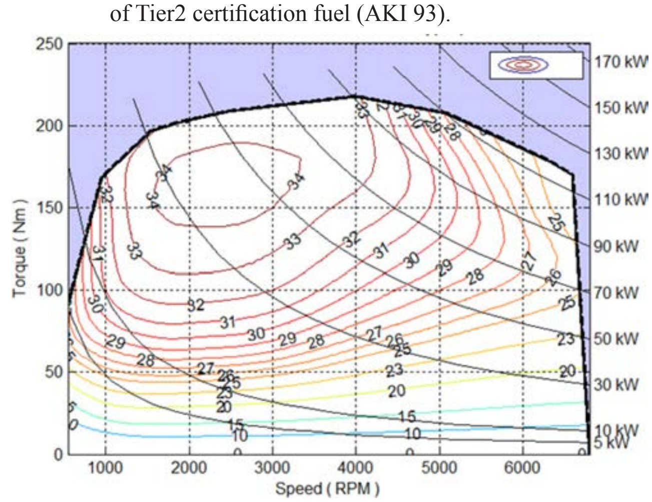

Figure 2. The thermal efficiency map for the I4 engine from a 2008 era Camry (derived from the I4 engine used in Ricardo baseline simulation for a standard car) (AKI 93 fuel)

b. ***2014 Naturally Aspirated Engine*** - A current production 2014 Mazda Skyactiv 2.0L 13:1 compression ratio naturally aspirated engine. The map in Figure 3 was generated from EPA's engine dynamometer testing using Tier2 certification fuel (AKI 93).

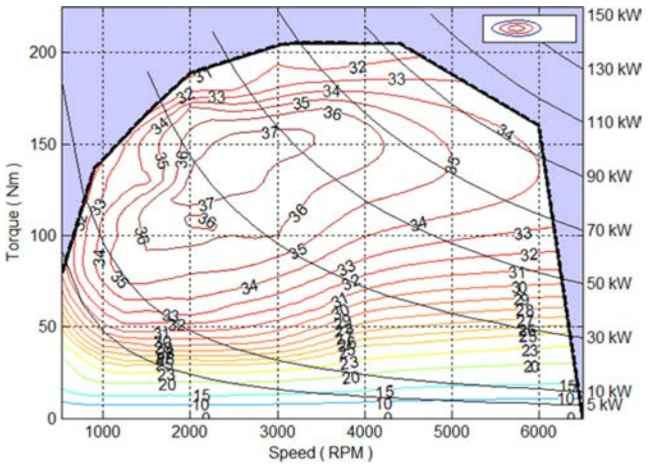

Figure 3. The thermal efficiency map for a 2014 Mazda 2.0L Skyactiv 13:1 compression ratio engine (AKI 93 fuel)

c. *Future 24-bar Turbo-Downsized engine* - The engine map in Figure 4 was derived (cropped the lug line back to 24-bar max) using the data & images from Ricardo's 27-bar turbocharged GDI engine with cooled EGR for large car applications in EPA's LD GHG rulemaking [3]. This future engine map assumes the use of Tier2 certification fuel (AKI 93).

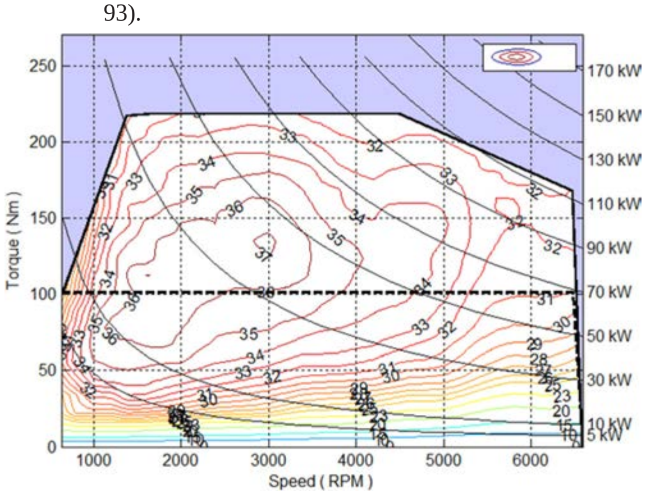

Figure 4. The thermal efficiency map for a future advanced 24-bar turbo-downsized engine (AKI 93 fuel)

2. **Extra fuel usage for other vehicle operating requirements** -one of the concerns raised about vehicle simulation models is that they tend to under predict fuel consumption (over predict fuel economy) because they often overlook fuel used to manage a vehicle's "overhead" functions, such as heavier transient operation, accessory interactions, torque transitions related to performance and drivability, special controls for emissions, and NVH reduction. One of the primary goals of EPA's extensive engine and vehicle benchmarking program is to identify appropriate modeling "rules" that can account for these overhead factors of actual vehicle implementations of GHG-reducing technologies. ALPHA already has imbedded rules to account for some of the most significant extra fuel use.

   - **NVH:** To generally avoid vehicle NVH issues, ALPHA applies rules to stay within industry operating norms. For example, a "cost" map approach was built into the ALPHAshift algorithm to discourage extended high-speed engine operation that might be undesirable for NVH reasons only to achieve a slight improvement in fuel economy [4].
   - **Transient engine operation:** In addition to using a steady-state engine fuel consumption map, ALPHA applies a transient fuel adjustment to properly account for reduced engine efficiency observed during heavier transient operation.
   - **Accessory loading:** All vehicles have basic power requirements to keep the vehicle running during the CO2 emissions/fuel economy cycles. EPA is collecting power data from both the alternator and battery during its vehicle benchmarking. ALPHA has the ability to model either specific transient accessory loads or to use a simpler average value. Most of the time the simple average technique is sufficient to estimate the CO2 emissions potential from a vehicle technology package. For example, EPA has observed that using an average accessory load of 300W is sufficient to adequately model the standard car vehicle class that utilizes alternator regen control.

     ALPHA applies these rules universally unless there is a specific reason to modify them. For example, when exploring use of a new technology like dual mass flywheels to enable further engine downspeeding or cylinder deactivation. A deeper discussion of this topic is beyond the scope of this paper. These general operating rules, along with additional ones, will be explored further in a future paper.

3. **Engine start-stop strategy:** Alpha contains a sub-model for 12 volt electrical start-stop technology, which simulates shutting the engine off after vehicle has stopped moving for 0.1 second. During a simulation, the start-stop mode is disabled when the vehicle is assumed to be operating cold such as during the first 100 sec of bag 1 of the FTP cycle.

Method for Engine Sizing to Maintain "Neutral" Vehicle Performance

Many fuel consumption reduction technologies decrease required wheel power, increase available engine power, or deliver power to the wheels more efficiently. If applied blindly, these technologies will reduce fuel consumption while also improving the vehicle's acceleration performance. NAS indicated in its 2011 *Assessment of Fuel Economy Technologies for Light-Duty Vehicles* that "objective comparisons of the cost-effectiveness of different technologies for reducing fuel consumption can be made only when the vehicle's performance remains equivalent." [18]

The simulation matrix uses three different engine maps representing real engines that have been mapped, or future engines that have been modeled. In order to apply these engine maps to a vehicle technology package, the engine map must be displacement adjusted so each technology package will maintain the same fundamental vehicle performance as the baseline vehicle. In addition, if the engines are not downsized along with road load reductions (weight, aerodynamic resistance and tire resistance reductions), then it will likely be too large and subsequently operate in less efficient areas of its fuel efficiency map.

Obviously there are a lot of ways to assess a vehicle's performance, but we were looking for a fairly simple method that did not place too much significance on a single performance metric. ALPHA estimates four different performance metrics when driving each vehicle package over a performance drive cycle (0-60 mph time, 30-50 mph time, 50-70 passing time, and ¼ mile time). For this standard car matrix analysis for this paper we settled with summing four performance metrics and comparing it to the sum of the performance metrics of the baseline vehicle (a 2008-era Camry) [7] [8].

To assure that the engine in each vehicle package in the standard car matrix maintains neutral performance, the engine displacement is adjusted so the vehicle package's performance metric sum falls reasonably close to the performance of the baseline vehicle. Proper engine sizing gets the vehicle package's performance close to neutral, allowing an effective comparison of the full GHG reduction merits of each technology. Engine resizing is necessary to maintain consistent neutral performance throughout the analysis for ALPHA to correctly estimate the full CO2 reduction benefits possible for each technology and its packaging.

Note: EPA's light-duty GHG emission regulation estimates the cost-effectiveness of low-GHG technologies needed to achieve the standards, with the assumption that vehicle performance would not decrease or increase as a result of the rule. EPA rules are developed with this assumption to accurately determine the cost-effectiveness associated with meeting the rule only. EPA's analyses do not include any other costs for added technology or improvements a manufacturer may choose to include for marketing or other reasons.

The approach taken for resizing the vehicle package's engine to maintain neutral performance this paper is to approximate the power at the wheels using iterative calculation rather than using iterative simulation which would provide a more realistic result while also increasing the simulation time, perhaps significantly [8]. For this reason the performance is not quite held perfectly neutral, however the results are still quite reasonable, typically within 3.5% of the baseline.

The engine map is first sized to match the basic power needs of the baseline standard car based on a scale factor determine by the following equation:

$$\begin{aligned}\text{Scale\_factor} = \text{Perf\_scale} &* (1 + \text{boost\_ratio} / 20.0)\\ &* (1 - \text{weight\_reduction\_pct} * 0.88)\\ &* (1 - \text{improve\_crr\_pct} * 0.02)\\ &* (1 - \text{improve\_aero\_pct} * .03)\end{aligned} \tag{2}$$

Where:

1. **perf_scale** is determined by analyzing the power curve of the baseline vehicle
2. **boost_ratio** is the ratio of the engine's boosted torque curve to its naturally aspirated torque curve
3. **weight_reduction_pct** is the percent of weight reduction for the simulation (e.g., 0%, 5%, 10%, 15%)
4. **improve_crr_pct** is the percent of rolling resistance reduction for the simulation (e.g., 0%, 10%, 20%)
5. **improve_aero_pct** is the percent of aerodynamic resistance reduction for the simulation (e.g., 0%, 10%, 20%)

Finally, the BSFC map was also adjusted so as not to overestimate the efficiency gain from using a smaller engine. As engine size is reduced, the cylinder surface area to volume ratio increases, which increases the relative heat losses and decreases efficiency. An adjustment factor, drawn from proprietary studies performed by Ricardo, Inc. [2] was used to scale the BSFC maps, resulting in a small increase in BSFC (a decrease in efficiency) for engines with smaller displacement.

5.0. Standard CAR Simulation Matrix Results

For each vehicle technology package, ALPHA estimates its CO2 gram per mile emissions from a "combined" two-cycle test (a weighted combination of cold-start city & highway results). Figure 5 shows a high level overview of the results for all 1080 CO2 values in the matrix, where the values are ordered in a regular fashion based on stepping through each matrix dimension in turn. This is not unlike the methodologies applied by the auto manufacturers when studying the effects of applying low-GHG technologies.

The "exemplar" vehicle technology package (known as the baseline package) is shown on the top left of the chart with 280.8 g/mile CO2. This package represents the configuration of the baseline vehicle mentioned in the light-duty GHG rule which only has a few low-GHG technologies (2008-era Toyota Camry with 2.4L engine and 5-speed transmission). The vehicle technology package with the most reduction of CO2 in the standard car matrix is shown on the lower right of the chart with a CO2 value slightly below 150 g/mile.

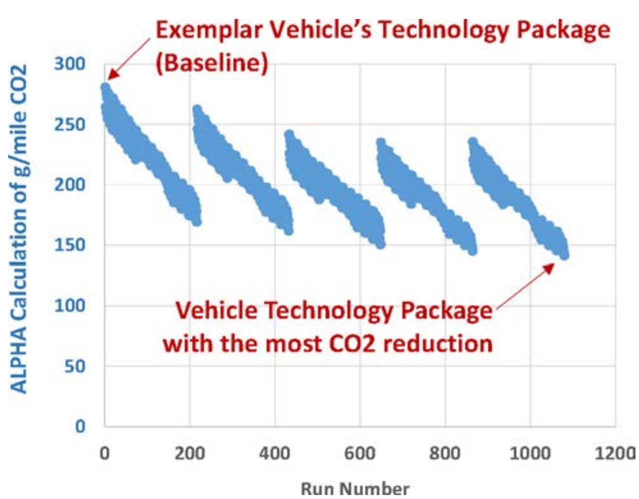

Figure 5. Overview of all 1080 of the CO2 values included in the Standard Car matrix

Understanding the effectiveness of each technology

One of EPA's key reasons for studying all the combinations of vehicle technologies in the standard car matrix is to assess and quantify the CO2 reduction effectiveness of each individual technology. Figure 6 shows that the percentage effectiveness of a given technology is dependent on the order in which it is added to a vehicle. In other words, the effectiveness of a specific technologies depends on which technologies have already been applied.

This chart shows two distinctly different sequences of adding seven unique technologies to a baseline 2008-era Camry. When the Skyactiv engine is the fourth technology added to the vehicle (Tech Walk A), the standard car matrix data shows it can reduce CO2 by 10.4%. When the Skyactiv engine is the first technology added to the vehicle (Tech Walk B), the data shows it only reduces the CO2 emissions by 12.3%. Looking closer at the content of each technology package one can begin to understand the reason for the difference. In Tech Walk A, the Skyactiv engine is added to a vehicle that contains a six-speed transmission, making it more effective then when it was added to a vehicle with only a four-speed transmission in Tech Walk B.

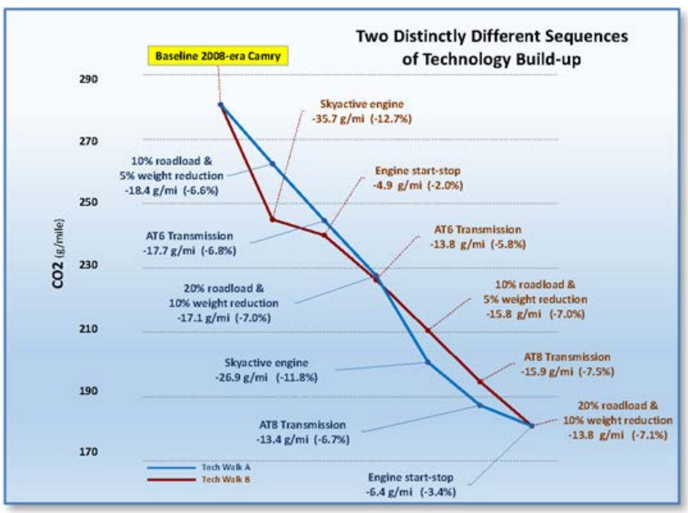

Figure 6. Two distinctly different application sequences of the same technologies - arriving at the same CO2 result (note that a larger copy of this graph is located in the Appendix)

Table 4 clearly shows how the effectiveness varies by the content of each vehicle package. Some technologies seem to have close to the same effectiveness independent of the order in which it is applied to a vehicle, such as roadload and weight reduction technology. While other technologies like engines and transmissions clearly show different effectiveness values are more sensitive to application order.

Table 4. Effectiveness for the same technology varies depending upon when it is applied to the vehicle

Technology	Tech Walk A		Tech Walk B	
	CO2 change	% change	CO2 change	% change
10% roadload & 5% weight reduction	-18.4	-6.6%	-15.8	-7.0%
AT6 Transmission	-17.7	-6.8%	-13.8	-5.8%
20% roadload & 10% weight reduction	-17.1	-7.0%	-13.8	-7.1%
Skyactiv engine	-26.9	-11.8%	-35.7	-12.7%
AT8 Transmission	-13.4	-6.7%	-15.9	-7.5%
Engine start-stop	-6.4	-3.4%	-4.9	-2.0%

Be aware that it is not just application order that affects a component's apparent effectiveness, because there is are synergy effects that must be considered when combining some technologies together in a vehicle package. This is noticeably apparent with advanced engine and transmission technologies both acting to reduce GHGs with a similar strategy. Advanced engines strive to have a larger maximum efficiency zone, known as the sweet spot. Advanced transmissions strive to enable the engine to operate in that optimal zone as much as possible. The end result of adding one or both of these new technologies to a vehicle package is that the vehicle operates in the sweet spot more often.

Therefore, when trying to estimate individual component effectiveness values, it is important to acknowledge that there can be synergy factors (most often negative synergy) that exist when including both a new engine and a new transmission in a vehicle package. The net effectiveness of including both a new engine and a new transmission in a vehicle package is not simply the product of the individual engine and transmission effectiveness values, but rather something less. The synergy effect for engines and transmissions is discussed later in the paper and illustrated in Table 7.

Vetting Matrix Results using a Simple Parametric Model

To better understand the overall effect of each technology included in the standard car simulation matrix, independent of order of application, the matrix data was carefully analyzed with an eye toward constructing a simple parametric equation model. The value of this simple equation was that the ALPHA CO2 emissions from each vehicle package could be viewed solely as a function of the technology in a package, making it easier to spot patterns (and any outliers) in this large dataset. This analysis presents an easy method of examining the percent effectiveness and any synergies from a baseline, which is nominally a 2008-era Camry with a 5-speed AT.

The intent of creating the parametric equation was to reduce the number of factors as much as possible, making a simple linear model. To that end, each of the technologies in the matrix were examined in turn to create the simplest form of the parametric equation. The parameters of the model were optimized to minimize the total root mean square error between the parametric equation and the original ALPHA matrix output.

The parametric equation starts with the CO2 value of the baseline vehicle (280.8 g/mi). The effects of the other various technologies included in the vehicle are either subtracted from or multiplied by this base value. The next few sections of the paper describe will walk through the steps taken to develop the equation and coefficients shown below:

$$\begin{aligned} CO2 = 280.8 * (1-Eff_{engine})*(1-Eff_{trans})*(1-Eff_{synergy}) \\ * (1-PctMass*1.005) + 89*PctMass \\ - 45*PctAero - 45*PctRolling - GmSS \end{aligned} \tag{3}$$

Where:

- 280.8 is the CO_2 g/mile emissions for the 5-speed baseline vehicle
- Eff_{engine}, Eff_{trans}, and $Eff_{synergy}$ are efficiency and synergy factors for the engine and transmission
- PctMass, PctAero, and PctRolling are the percent reduction in mass, aerodynamic loads, and rolling resistance (respectively)
- GmSS is the reduction in grams of CO_2 for each engine-transmission combination

This parametric estimation is not intended to replace robust simulations from ALPHA, but rather to summarize the results of the modeling runs for illustrative and quality control analysis purposes. This type of analysis will also be helpful when eventually vetting the data used for EPA's midterm evaluation for the light-duty GHG rule.

Effectiveness of Reducing Road Loads

Aerodynamic Drag

$$CO2 = 280.8 * (1-Eff_{engine})*(1-Eff_{trans})*(1-Eff_{synergy}) * (1-PctMass*1.005) + 89*PctMass - \mathbf{45*PctAero} - 45*PctRolling - GmSS \tag{4}$$

To examine the reductions in aerodynamic resistance, each package in the matrix with a base aero load was paired with the packages having a 10% reduction in aero load, but the same collection of other technologies. The difference in combined cycle CO_2 between each pair of runs (without aero reduction and with 10% aero reduction) was calculated; the results for all pairs of runs are shown in Figure 7.

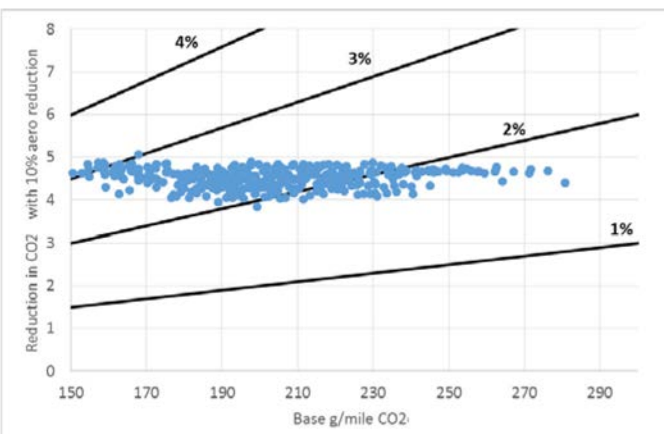

Figure 7. Effectiveness of a 10% reduction of aerodynamic drag

A reduction of 10% in aero loads reduces the combined cycle CO_2 by an average of 4.5 grams/mile with a scatter of ±0.7g/mi. This number is substantially independent of the base combined cycle CO_2, but does vary slightly depending on the engine and transmission combinations used.

To get a sense of the CO_2 reduction in "percent" versus "g/mile", black lines have been added to the chart for reference. These constant lines show the percent reduction as a function of baseline CO_2 g/mile (x-axis). For example, a 1% reduction in CO_2 for a baseline vehicle with a starting point of 300 g/mile is equal to 3 g/mile. While a 1 percent reduction in CO_2 for a vehicle with a starting point of 150 g/mile is equal to 1.5 g/mile. These black "percentage" lines have also been added to Figure 8 and Figure 9.

As expected, the average reduction in GHG scales with percentage reduction in aero loads, so that a 20% reduction in aero loads yields an average of 9.0 grams/mile CO_2 reduction (twice the of 4.5 grams/mile reduction at 10%). Thus, the effect of applying a reduction in aero dynamic loading is to reduce CO_2 emissions by 45 g/mi times the percent of aero reduction, leading to the factor in the final parametric equation.

Rolling Resistance

$$CO2 = 280.8 * (1-Eff_{engine})*(1-Eff_{trans})*(1-Eff_{synergy}) * (1-PctMass*1.005) + 89*PctMass - 45*PctAero - \mathbf{45*PctRolling} - GmSS \tag{5}$$

A similar methodology was used to examine the effect of reducing tire rolling resistance. The results, showing the difference between packages with 10% reduction in rolling resistance and those with baseline rolling resistance, are shown in Figure 8. In this case, reducing rolling resistance by 10% also yielded a 4.5 grams/mile reduction in CO_2 with a scatter of ±0.7g/mi. Again, this result was substantially independent of the base combined cycle CO_2 but varied slightly with different engine and transmission combinations.

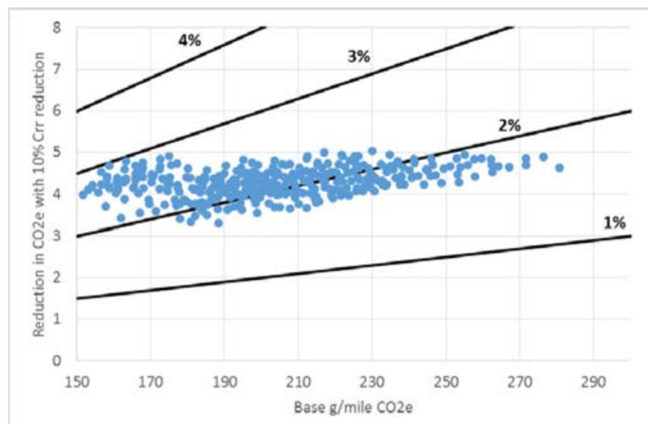

Figure 8. Effectiveness of a 10 % reduction of tire rolling resistance

Weight Reduction

$$CO2 = 280.8 * (1-Eff_{engine})*(1-Eff_{trans})*(1-Eff_{synergy}) \mathbf{* (1-PctMass*1.005) + 89*PctMass} - 45*PctAero - 45*PctRolling - GmSS \tag{6}$$

A similar methodology was used to examine the effect of weight reduction. However, rather than resulting in an approximately constant reduction in CO_2, the results varied as a function of the base combined cycle CO_2 due to the close tie between weight and acceleration performance, as shown in Figure 9. Although there is again some scatter, the reduction in combined CO_2 is roughly linear (with a slight variation with engine-trans combination), with a total reduction of [0.1005*(base CO2) - 8.9] g/mile for a 10% reduction in mass. The actual result again varied slightly with different engine and transmission combinations.

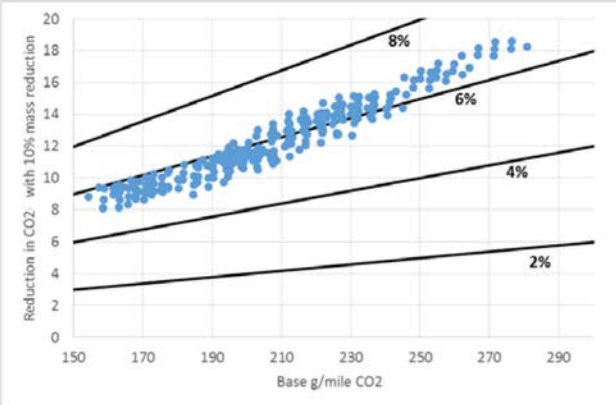

Figure 9. Effectiveness of a 10% reduction of vehicle weight

Effectiveness of Changing Engines and Transmissions

$$CO2 = 280.8 * (1\text{-}Eff_{engine})*(1\text{-}Eff_{trans})*(1\text{-}Eff_{synergy}) * (1\text{-}PctMass*1.005) + 89*PctMass - 45*PctAero - 45*PctRolling - GmSS \quad (7)$$

With the road loads accounted for, the effects of the various engines and transmissions were examined. Because the engine and transmission are coupled in the drivetrain, it was expected that the effectiveness of the engine and transmission would generally be coupled, such that the percentage reduction of any given engine-transmission pair would be different from that of the engine and transmission independently. Thus, three factors were defined:

- Engine effectiveness (Eff_{engine}), representing the percent decrease of CO2 solely due to the engine
- Transmission effectiveness (Eff_{trans}), representing the percent decrease of CO2 solely due to the transmission
- Effectiveness "synergy factor" ($Eff_{synergy}$), representing the additional percent decrease of CO2 when a given engine and transmission are paired

The combined cycle CO2 of a given engine-transmission pair is the product of the engine effectiveness, the transmission effectiveness, and the "synergy factor":

$$CO2 = (CO2_{baseline}) * (1\text{-}Eff_{engine})*(1\text{-}Eff_{trans})*(1\text{-}Eff_{synergy}) \quad (8)$$

When an advanced engine and transmission are paired, the expectation is that the total CO2 reduction would be less than what would be obtained when considering the effect of each independently (essentially, individually they each compete to save the same fuel). Thus, the "synergy factor" ($Eff_{synergy}$) would be expected to be negative, *increasing* the net CO2 result.

Although this methodology results in three separate factors (engine effectiveness, the transmission effectiveness, and the "synergy factor") rather than a single engine-transmission pair effectiveness factor, it does add some insight by generally apportioning the effectiveness to each component.

As an example, CO2 results for each combination of engine and transmission (with no other technologies in the packages) are shown in Table 5. Note that the baseline Camry CO2 estimate (NA Camry engine w/5AT) matches well with EPA Certification results (280.8 g/mi versus 283g/mi).

Table 5. ALPHA CO2 results, pairing different engines and transmissions without additional technologies applied.

g/mile CO2e	Baseline NA Camry	2014 Skyactiv 13:1	Future TDS 24-bar
2008 5AT	280.8	245.1	212.4
2013 6AT	262.3	230.4	203.2
2014 8AT	241.5	215.1	193.2
2020 Future 8AT	234.8	207.7	180.2
2020 Future 8DCT	235.2	204.3	175.1

To determine the individual effectiveness and synergy factors for each pair of engines and transmissions, the CO2 results for all technology packages in the matrix were paired with the corresponding baseline package (NA Camry engine w/5AT) and the average percentage difference calculated. There was some scatter associated with the variation in road load (as expected, since the effect of engine-transmission pairs on road load CO2 reduction was noted earlier in the road load section. The total powertrain effectiveness percentages are shown in Table 6. The corresponding synergy factors are given in Table 7.

Table 6. ALPHA CO2 results, total effectiveness results when changing engines and transmissions, measured against the baseline Camry (NA Camry engine w/ 5AT).

Total Effectiveness	Baseline NA Camry	2014 Skyactiv 13:1	Future TDS 24-bar
2008 5AT	0.0%	12.7%	24.4%
2013 6AT	6.6%	18.0%	27.7%
2014 8AT	14.0%	23.4%	31.1%
2020 Future 8AT	16.4%	26.0%	35.8%
2020 Future 8DCT	16.2%	27.2%	37.6%

Table 7. ALPHA CO2 results, synergy factor results when changing engines and transmissions, measured against the baseline Camry (NA Camry engine w/ 5AT).

Total Effectiveness	Baseline NA Camry	2014 Skyactiv 13:1	Future TDS 24-bar
2008 5AT	0.0%	0.0%	0.0%
2013 6AT	0.0%	-0.5%	-1.7%
2014 8AT	0.0%	-1.5%	-3.8%
2020 Future 8AT	0.0%	-1.0%	-0.9%
2020 Future 8DCT	0.0%	+0.3%	+1.0%

Effectiveness of engine start-stop

$$CO2 = 280.8 * (1\text{-}Eff_{engine})*(1\text{-}Eff_{trans})*(1\text{-}Eff_{synergy}) * (1\text{-}PctMass*1.005) + 89*PctMass - 45*PctAero - 45*PctRolling - GmSS \quad (9)$$

Finally, the effect of engine stop-start was considered. Since the stop-start function essentially eliminates GHG production during idle, it was expected that only two items would affect the parametric value:

1. Choice of engine, which affects idle fuel rate
2. Choice of transmission, which affects idle torque requirement

The reduction in CO2 due to start-stop technology (GmSS) for each engine-transmission pair was calculated, with results shown Table 8.

Table 8. ALPHA's net CO2 reduction with engine start-stop technology

Stop/start reduction in CO2	Baseline NA Camry	2014 Skyactiv 13:1	Future TDS 24-bar
2008 5AT	16.7	5.9	9.8
2013 6AT	16.4	5.2	9.2
2014 8AT	16.3	7.6	12.2
2020 Future 8AT	13.4	2.8	4.0
2020 Future 8DCT	14.6	2.5	3.6

The numbers presented in Table 8 highlight the utility of creating a parametric model. Note that stop-start engine technology has high value with less efficient baseline Camry engine and it has less value with the 2014 Skyactiv engine. Also notice that stop-start has lower value with the more advanced transmissions.

Comparing the 2020 Future 8AT to the 2014 8AT when paired with the baseline NA Camry engine shows that start-stop technology is about 3g/mile less effective when implemented on the more advanced 2020 transmission. This result would be expected, as the 2020 transmission has lower spin losses, requires reduced engine power at idle, and thus has less fuel available to be "saved" with a start-stop system. There is a similar differential between the two eight-speed transmissions paired with the 2014 Skyactiv engine.

However, with the future TDS 24-bar engine, start-stop technology is about 8g/mile less effective when comparing the 2020 Future 8AT transmission (4.0 g/mile) to the 2014 8AT transmission (12.2 g/mile). This discrepancy highlights an area that should be explored further during the QC process. After further investigation, it became apparent that the future TDS 24-bar engine fuel consumption map was inconsistent in a small area around idle, resulting in wide variations in calculated fuel usage at similar torque points. While this particular issue is relatively subtle, use of the parametric breakdown of results made it easier to detect the issue in the QC process.

The Parametric Model

All the parameters of the parametric model were combined into a single parametric equation. The factors in this equation were calculated to minimize the total root mean square error between the parametric model and the original ALPHA matrix output. The resulting equation was:

$$CO2 = 280.8 * (1\text{-}Eff_{engine})*(1\text{-}Eff_{trans})*(1\text{-}Eff_{synergy}) * (1\text{-}PctMass*1.005) + 89*PctMass - 45*PctAero - 45*PctRolling - GmSS \quad (10)$$

Where:

- 280.8 g/mile is the CO2 emissions for the 5-speed baseline vehicle
- the Eff_{engine}, Eff_{trans}, and $Eff_{synergy}$ factors are shown in Table 6 and Table 7
- PctMass, PctAero, and PctRolling are the percent reduction in mass, aerodynamic loads, and rolling resistance (respectively)
- GmSS is the reduction in grams of CO2 for each engine-transmission combination shown in Table 8

For the entire standard car simulation matrix, the parametric model matches the original ALPHA output within ±2 grams/mile CO2e for all 1080 runs, and within ±1 gram/mile CO2e for 91% of the runs. Figure 10 shows the ALPHA output versus the corresponding parametric result for all runs in the standard car matrix.

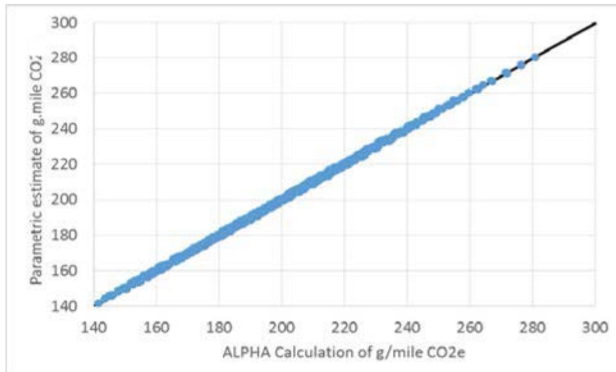

Figure 10. Comparison of the Parametric Equation estimates to the ALPHA CO2 results

The accuracy of the parametric model depends on the number of factors include in the equation. For example, as noted above, the effect of road load reductions vary slightly depending on the engine and transmission combination. Additional factors accounting for the coupling of road loads and engine-transmission pairs could be added to the parametric model; doing so would improve the accuracy of the equation and reduce the difference between the ALPHA outputs and the parametric model further so that nearly 99% of the runs would fall within ±1 gram/mile CO2. However, this comes at the expense of a more complex parametric model.

The parametric model was helpful for simplifying the ALPHA results to a small number of parameters, which can be used to evaluate the quality of the ALPHA output or to understand the relative effects of each technology component included in the matrix.

6.0. Sample "Best-Available" Package Walk

The parametric equation technique was used as a quality inspection tool to help examine the standard car matrix results, making sure that the effectiveness of each technology seemed appropriate. After completing the data quality review using the parametric equation tool, it became possible to explore any number of distinct "package walks" through the results in the matrix. Each technology walk reveals the stepwise CO2 results that are possible as a manufacturer uniquely upgrades a baseline vehicle with new advanced technologies.

Note: These modeling results illustrate how much CO2 reduction is possible with the assumption that vehicle performance would not decrease or increase as a result of the rule. EPA rules are developed with this assumption to accurately determine the cost-effectiveness associated with meeting the rule only. These modeling results do not estimate any efficiency impacts associated with technology changes a manufacturer may choose to include for marketing or other reasons.

Figure 11 summarizes one possible package walk that contains ALPHA's CO2 estimates of adding 9 different vehicle technologies to the baseline vehicle. The technology packages represented by each of the steps (B-J) are described in Table 9. This set of technology packages represent one of several feasible paths for a manufacturer to progress from a 2008-era standard car like a Camry to one that is potentially able to approach or exceed its 2025 footprint-based target.

The gray bar on the right in Figure 11 shows the CO2 compliance target value (152.3 g/mile) for a 47.75 ft^2 standard car in model year 2025, prior to any GHG credit adjustments. This value was derived from the data for chart in Figure 12 (from the LD GHG rule) [14]. Based on the assumed footprint of 47.75 ft^2, this model year 2025 standard car would have to emit less than 152.3 g/mile of CO2 over the combined FTP and HWFE test cycles to be in compliance.

However, this CO2 compliance target can be adjusted based on the manufacturer's anticipated application of various off-cycle and air conditioning GHG credits which are part of the LD GHG rule [14]. The second green bar from the left in Figure 11 represents the adjusted value of the 2025 CO2 target (178.0 g/mile) for an average sized model year 2025 standard car with a footprint size of 47.75 square feet. That value includes an estimated amount of 25.7 g/mi of air conditioning and off-cycle credits that are predicted to be available to manufacturers of standard cars in 2025. The green bar on the far left of the chart represents the credit adjusted value of the 2021 CO2 target (203.9 g/mile) for this sized standard car in 2021.

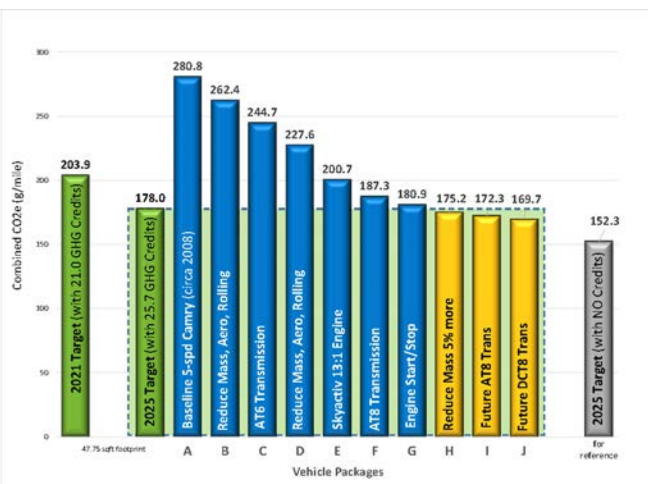

Figure 11. ALPHA's CO2 emission estimates for 9 different vehicle technology packages (note that this figure is repeated as a larger chart in the Appendix)

The blue bars in Figure 11 represent the CO2 emission values from different packages, showing the effects on CO2 results as each of 9 "best available" technologies are incrementally added to the standard car. Best available technologies are exceptional ones that have been encountered in vehicles being sold in the market in 2014/2015.

The orange bars in the chart represent the potential CO2 results possible when adding some future weight reduction and transmission technologies being developed by manufacturers and suppliers to the standard car package.

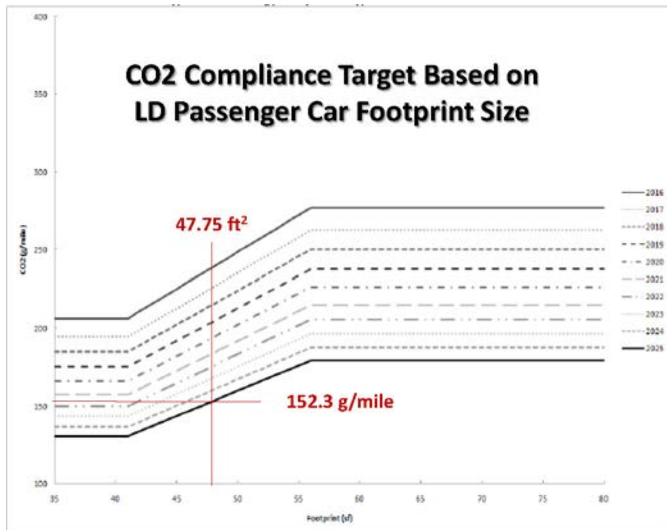

Figure 12. GHG Emissions Target for a 2025 model year standard sized car

Table 9. Definition of best-available technology packages

A	**Null Vehicle:** Baseline 2.4L Camry I4 engine, 4-speed automatic transmission
B	**Baseline 2008 Camry:** Baseline 2.4L I4 Camry engine, 5-speed automatic transmission
C	**Reduce Mass, Aero, Rolling Resistance:** Baseline 2.4L I4 Camry engine, 5-speed automatic transmission, 5% reduction of mass, 10% reduction of aerodynamic resistance, 10% reduction of rolling resistance
D	**AT6 Transmission:** Baseline 2.4L I4 Camry engine, 6-speed automatic transmission, 5% reduction of mass, 10% reduction of aerodynamic resistance, 10% reduction of rolling resistance
E	**Reduce Mass, Aero, Rolling Resistance:** Baseline 2.4L I4 Camry engine, 6-speed automatic transmission, 10% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance
F	**Skyactiv Engine:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, 6-speed automatic transmission, 10% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance
G	**AT8 Transmission:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, 8-speed automatic transmission, 10% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance
H	**Engine Start/Stop:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, 8-speed automatic transmission, 10% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance, start-stop engine technology
I	**Future Additional 5% Mass Reduction:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, 8-speed automatic transmission, 15% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance, start-stop engine technology
I	**Future AT8 Transmission:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, "future" 8-speed dual-clutch transmission, 15% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance, start-stop engine technology
J	**Future DCT8 Transmission:** Skyactiv 2.0L 13:1 compression ratio I4 Skyactiv engine, "future" 8-speed dual-clutch transmission, 15% reduction of mass, 20% reduction of aerodynamic resistance, 20% reduction of rolling resistance, start-stop engine technology

Observations from this Best-Available Package Walk

While our technology analysis is still an on-going process, the extensive in-depth vehicle and engine testing behind the modeling and analysis has yielded a deep understanding of vehicle operation and the basic strategic control "rules" that manufacturers define for their vehicles utilizing these new technologies. The numerous ALPHA validations that have been performed, and the knowledge about the controls, have given us confidence that we understand many of the integration issues that manufacturers must consider if they were to combine best-available technologies together to estimate future CO2 emissions. Development of this standard car matrix approach has proven itself to be a very useful tool for EPA to compare hundreds, if not thousands, of vehicle technology packages.

Our preliminary analysis of the standard car matrix and the specific vehicle package walk shown in Figure 11, lead us to consider the following two hypotheses, both of which still need to be proven, or disproven through more vehicle testing and analysis prior to the completion of the midterm evaluation for the 2022-2025 standards.

Hypothesis #1

A standard (midsize) car configured with only existing best-available technologies in 2014/2015, represented by the blue bars, comes very close to achieving its 2025 LD GHG footprint-based target with 25.7 g/mi of air conditioning and off-cycle credits (green box).

Hypothesis #2

A standard (midsize) car configured with feasible future technologies, like the engines and transmissions represented by the yellow and orange bars, is capable of meeting and possibly exceeding its 2025 LD GHG footprint-based target with 25.7 g/mi of air conditioning and off-cycle credits (green box).

The list of technologies examined in this study represent only a few of the pathways likely to be available in the 2025 timeframe. Additional technologies are available and emerging today, including powertrain electrification, continuously variable transmissions, and accessory load reductions which will play important roles in manufacturers' technology plans for the 2022-2025 model years.

Whenever we have encountered incomplete data or have limited understanding of some operational or technical aspect of these technologies, such as a vehicle's fuel usage during extreme periods of transient operation, we have tried to make conservative assumptions for fuel usage. We are committed to continue testing and modeling enhancements to help us learn even more about these new and emerging technologies.

The analysis presented in this paper is strictly a technical analysis looking at the CO2 results of implementing various technology packages. It is important to remember that this study did not look at business case issues that affect manufacturers' technology planning, such as stranded capital, current product plans, imbedded company expertise, consumer acceptance, manufacturing costs, availability of materials, production capacity, effect of product cycles, sharing of components across car lines, and customer willingness to pay.

7.0. Summary - Conclusion/Future Work

Conclusion

The work discussed in this paper has given EPA the ability to use its ALPHA model to estimate the CO2 g/mile reductions that are possible from grouping combinations of current and future powertrain and vehicle technologies. EPA found it could:

- Use key engine fuel maps, transmission maps, and operational control data acquired from benchmarking 2013, 2014, and 2015 vehicles to validate its ALPHA model.
- Easily create and study the potential CO2 reduction benefits that come from creating various combinations of the best of these technologies, not only in a standard (midsized) car, but in SUVs and light-duty trucks as well.
- Develop a parametric analysis technique which proved valuable as a quality tool.
- Compare the CO2 results from large numbers of vehicle technology packages to investigate the operation of the ALPHA model and validate its computational methods.
- Create sample technology walks to easily illustrate and communicate potential pathways available for manufacturers to evolve their vehicle systems through successively adding CO2 reduction technologies.

Future Work

EPA's review of public and confidential information shows that there are more emerging technologies that will likely become cost-effective for vehicles in the 2022-2025 timeframe, and will lead to more pathways to achieving the targets for the LD GHG standards.

- This paper is a status of EPA's on-going ALPHA development work using data available at the time of writing. EPA plans to continue its benchmarking and validation of the ALPHA model using data from additional MY2015, MY2016 and MY2017 vehicles and engines.
- Of special interest is evaluation of future emerging engine technologies, particularly engines that involve cooled EGR, cylinder deactivation, as well as Miller, Atkinson and HCCI cycles.
- EPA plans to continue its matrix analysis, adding matrices for small cars, SUVs, and light-duty trucks, to inform its comprehensive assessment of low GHG technologies for the light-duty midterm analysis for model years 2022 - 2025.
- EPA plans to also continue its evaluation of emerging transmission technologies including advances in CVTs, DCTs, vehicle electrification, and road load reductions.

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Contact Information

Dan Barba
National Center for Advanced Technology
US EPA - Office of Transportation & Air Quality
barba.daniel@epa.gov

John J. Kargul
National Center for Advanced Technology
US EPA - Office of Transportation & Air Quality
kargul.john@epa.gov

Andrew Moskalik
National Center for Advanced Technology
US EPA - Office of Transportation & Air Quality
moskalik.andrew@epa.gov

Definitions/Abbreviations

ALPHA - Advanced Light-Duty Powertrain and Hybrid Analysis

ANL - Argonne National Lab

BMEP - Brake mean effective pressure

BSFC - Brake specific fuel consumption

EPA - Environmental Protection Agency

FTP - Federal Test Procedure (the "city cycle")

GHG - Greenhouse gas

HWFET - Highway Fuel Economy Test (the "highway cycle")

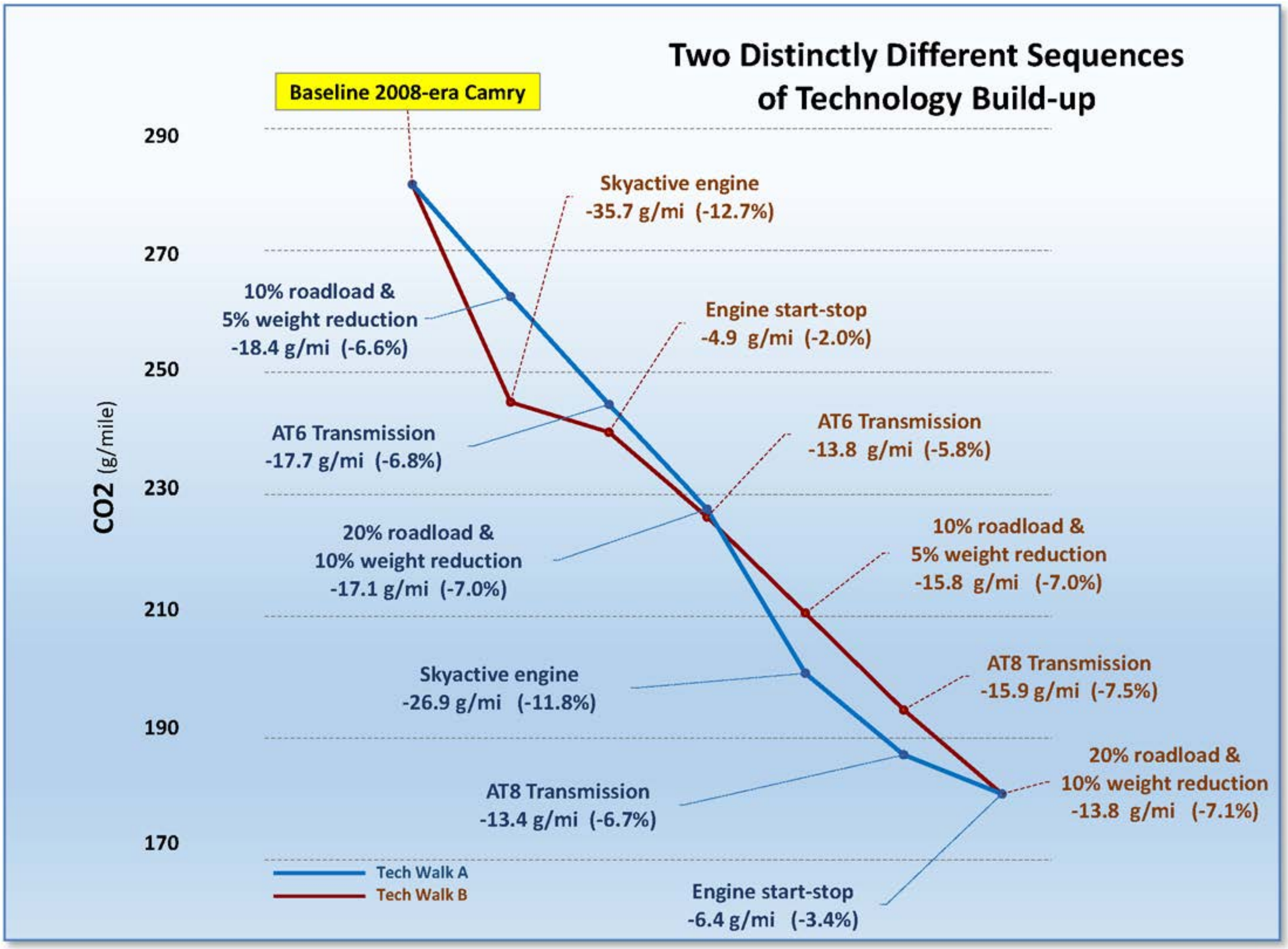
mpg - Miles per Gallon

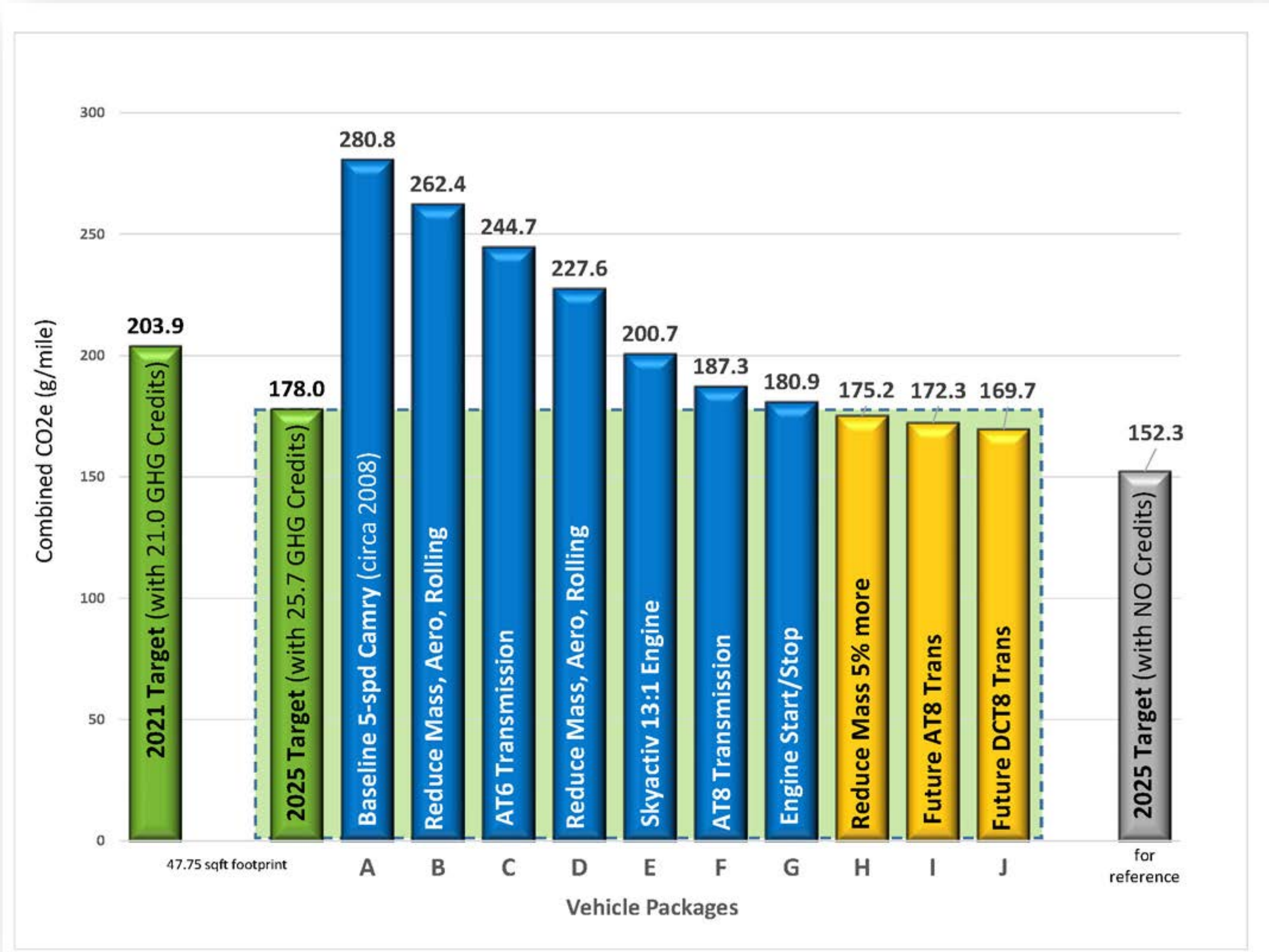
NVFEL - National Vehicle and Fuel Emissions Laboratory

UDDS - Urban Dynamometer Driving Cycle

ZF - ZF Friedrichshafen AG, a transmission supplier

APPENDIX


Two Distinctly Different Sequences of Technology Build-up
Baseline 2008-era Camry
CO2 (g/mile)
290
270
250
230
210
190
170
Skyactive engine -35.7 g/mi (-12.7%)
10% roadload & 5% weight reduction -18.4 g/mi (-6.6%)
Engine start-stop -4.9 g/mi (-2.0%)
AT6 Transmission -17.7 g/mi (-6.8%)
AT6 Transmission -13.8 g/mi (-5.8%)
20% roadload & 10% weight reduction -17.1 g/mi (-7.0%)
10% roadload & 5% weight reduction -15.8 g/mi (-7.0%)
Skyactive engine -26.9 g/mi (-11.8%)
AT8 Transmission -15.9 g/mi (-7.5%)
20% roadload & 10% weight reduction -13.8 g/mi (-7.1%)
AT8 Transmission -13.4 g/mi (-6.7%)
Tech Walk A
Tech Walk B
Engine start-stop -6.4 g/mi (-3.4%)



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