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# Characterization of GHG Reduction Technologies in the Existing Fleet

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## Abstract

By almost any definition, technology has penetrated the U.S. light-duty vehicle fleet significantly in conjunction with the increased stringency of fuel economy and GHG emissions regulations. The physical presence of advanced technology components provides one indication of the efforts taken to reduce emissions, but that alone does not provide a complete measure of the benefits of a particular technology application. Differences in the design of components, the materials used, the presence of other technologies, and the calibration of controls can impact the performance of technologies in any particular implementation. The effectiveness of a technology for reducing emissions will also be influenced by the extent to which the technologies are applied towards changes in vehicle operating characteristics such as improved acceleration, or customer features that may offset mass reduction from the use of lightweight materials.

This paper begins with an examination of trends in the penetration of key advanced technologies into the U.S. light-duty vehicle fleet. We then investigate the overall influence of these technologies and vehicle changes on tailpipe $CO_2$ emissions using metrics for powertrain efficiency and tractive energy metrics. Finally, we introduce a methodology for representing existing technology implementations across the full fleet of non-electrified vehicles using EPA's Advanced Light-duty Powertrain and Hybrid Analysis (ALPHA) full vehicle simulation model and library of benchmarked powertrain component models. Using such an approach, a compliance analysis can be conducted for a future vehicle fleet where the emissions reductions and associated costs are applied incrementally to the existing set of baseline fleet of vehicles, while giving appropriate consideration to how a particular vehicle's technology implementation influences the potential for further emissions reductions.

## Introduction

In previous assessments of technology effectiveness for greenhouse gas (GHG) emissions reduction, the U.S. Environmental Protection Agency (EPA) utilized a lumped parameter model (LPM) to assign the effectiveness of future technologies. [3] In public comments, some industry stakeholders suggested that replacing the LPM with a process more directly tied to full vehicle simulation would result in a more robust analysis of potential $CO_2$ reduction. To explore one potential approach to expand (and more directly use) full vehicle simulations in its modeling methodology, this paper examines use of full vehicle simulation modeling to better characterize the technology in the baseline vehicle fleet. Careful characterization of the technologies contained in the baseline fleet of vehicles is needed to calculate future vehicle's $CO_2$ reduction for the analysis of fleet GHG compliance. A companion paper explores expanded (and more direct) use of full vehicle simulation modeling to characterize the effectiveness of advanced technologies in future fleets [5].

In any analysis of future GHG standards for light-duty vehicles, EPA evaluates the costs and benefits of achieving compliance with the addition of emissions-reducing technologies, measured relative to a reference case where the standards are held constant. In 2012, the rulemaking analysis conducted for MYs 2017-2025 GHG standards, used data from MYs 2008 and 2010 to define baseline fleets, from which the benefits of adding emissions-reducing technologies were assessed.

More recently, EPA has been continuously monitoring the state of technologies as part of the Midterm Evaluation of the MYs 2022-2025 GHG standards, including analyses for MYs 2014, 2015, and 2016 baseline fleets. As can be seen in Figure 1, in the years since the GHG rule was finalized in 2012, the penetration of key technologies has increased significantly. These penetrations account for not only initial implementations of technologies, but also subsequent iterations and refinements in second generation technologies or beyond in some cases.

Figure 2 shows the technological advancements for several engine categories using specific horsepower as a proxy for innovation. Over the past several decades, naturally aspirated (NA) and boosted engines have undergone steady advancements in specific power. Even given this overall trend, a significant variation exists among vehicles

**FIGURE 1** Powertrain technology penetration trends in the U.S. light-duty fleet (note: dashed lines are projected data)

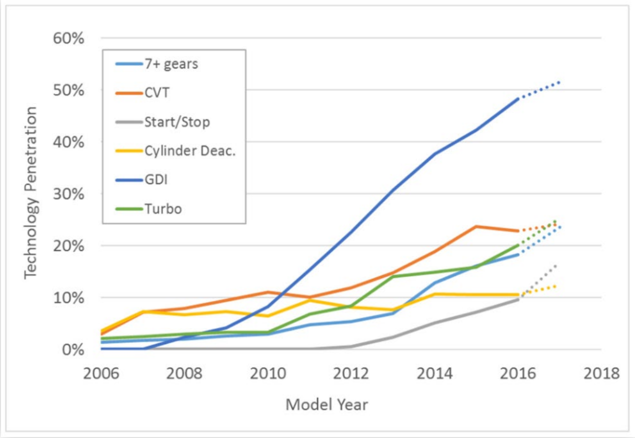

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**FIGURE 2** Trends in specific horsepower for select engine technologies. Data source: [1], U.S. light-duty fleet, non-hybrid gasoline vehicles.

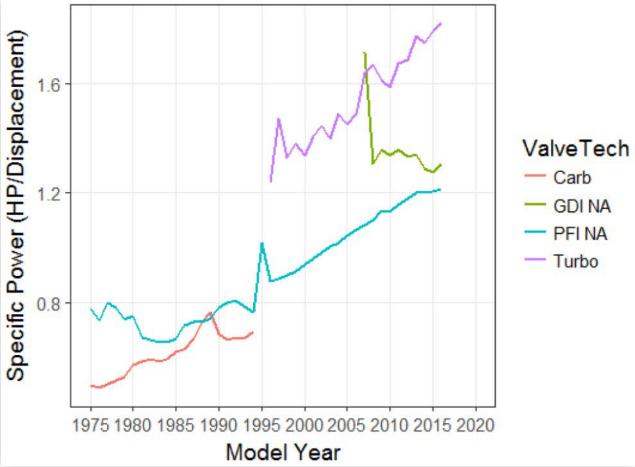

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**FIGURE 3** Variation of specific power in the MY2016 fleet. Rectangles indicate range of data between 25th and 75th percentiles; Bars indicate 10th and 90th percentiles. Data source: [1], U.S. light-duty fleet, non-hybrid gasoline vehicles.

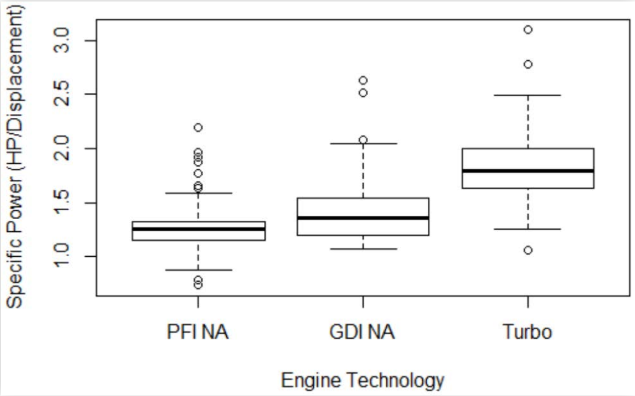

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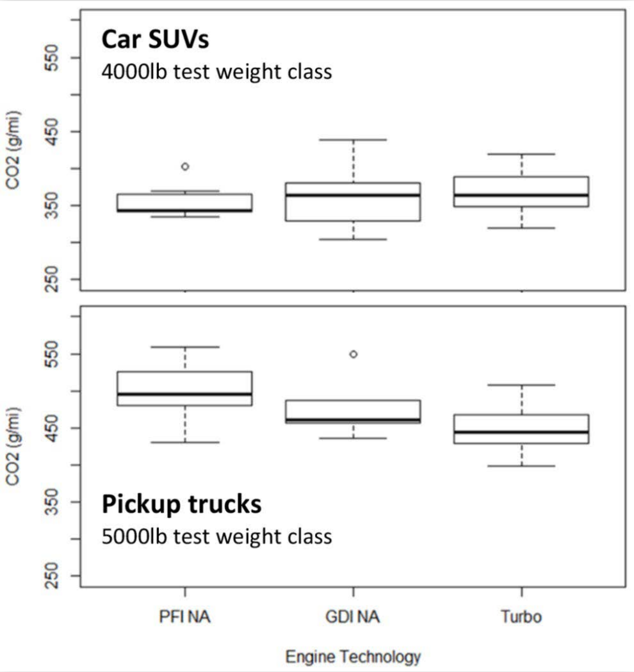
**FIGURE 4** Example variation of tailpipe CO2 for MY2016 SUVs (top), and pickup trucks (bottom) Rectangles indicate range of data between 25th and 75th percentiles; Bars indicate 10th and 90th percentiles. Data source: [1], U.S. light-duty fleet, non-hybrid gasoline vehicles.



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for any given model year. As shown Figure 3, specific power can vary by up to a factor of two within an engine technology category. Similar variation in combined cycle tailpipe $CO_2$ is shown in Figure 4 for 4000 lb sport utility vehicles (SUVs) and 5000 lb pickup trucks. While all of this variation cannot be entirely attributed to differences in technology implementation, the large degree of variation is a reason to be cautious when characterizing existing vehicles using only the descriptions provided by broadly defined technology categories.

The following sections begin with a description of how the data collected by EPA for compliance purposes, together with information from other sources including laboratory vehicle benchmarking, are used to calculate various metrics for vehicle and technology characteristics that are related to fuel economy and GHG emissions. Next, key vehicle and technology characteristics are presented, with a focus on model years (MYs) 2012-2016. Since tailpipe $CO_2$ emissions are a function of both the operation of the powertrain and the vehicle road loads over the test cycle, trends in both powertrain efficiency and tractive energy intensity are presented for these five model years. Finally, a methodology is presented for using EPA's ALPHA full vehicle simulation tool and library of benchmarked powertrain component models to characterize technology implementations across the full fleet of non-electrified conventional vehicles.

# Assembling the Data for Fleet-wide Technology Characterization

Vehicle specification data that is relevant to characterizing emissions-reducing technologies are available from multiple sources. Because these data sources were generally not originally developed for this particular use, any single source will often provide only partial coverage of vehicle models over the years of interest, and production volume data necessary for generating aggregate statistics is often lacking. This section describes a methodology for consolidating data from multiple sources, while maintaining the integrity of the original data.

The most basic obstacle to consolidating data sets is variation in how vehicles are classified in different data sources. This might include variation in the level of detail as well as variation in the particular dimensions along which vehicles are characterized. Even when various data sets share a common categorization method, merging multiple sources may still be complicated when one or more of the data set does not include the entire range of vehicles.

## Data Sources

The primary data source used by EPA to characterize the GHG performance of the existing fleet is the certification data submitted by manufacturers to EPA's VERIFY database. The data pertain mainly to vehicle emissions performance collected in dynamometer testing, and include a general classification of engines, transmissions, and drive systems. Also included are vehicle characteristics related to road loads: dynamometer target and set coefficients, road load horsepower, and test weights. Additional data is obtained from EPA's Test Car database, which is publicly available.

In addition to the information in datasets maintained by EPA, additional vehicle specifications and technology details can be obtained through other public and commercially available sources of vehicle data such as Edmunds.com©, Wards Automotive (Penton©) and AllData Repair (AllData LLC©).

## Merging Data Sources

**Definition of a Primary Key** In order to query the data contained in these various data sources, a primary key to relate entries in different sources to each other is defined. This allows each vehicle entry to have the maximum possible level of detail pertaining to vehicle characteristics while also allowing for the assignment of vehicle production volumes for subsequent data averaging and synthesis.

The vehicle engines are categorized based on layout, number of cylinders, displacement, as well as the definitions of method of air aspiration and fuel type as shown in Table 1 and Table 2.

Vehicle transmissions are categorized according to their type and number of speeds as shown in Table 3.

**TABLE 1** Engine Boosting Categorization

| TC | Turbocharged engines without any method of supercharging. Includes twin turbocharging |
|---|---|
| SC | Supercharged engines without any method of turbocharging |
| TS | Engines with both turbocharging and supercharging |
| NA | Naturally Aspirated Engines |
| Null | Electric Vehicles |

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**TABLE 2** Fuel Type Categorization

| G | Gasoline. Includes gasoline runs of both flex-fuel vehicles and REEVs |
|---|---|
| D | Diesel |
| E | Electricity. Includes BEVs, hydrogen fuel cell vehicles and REEV runs using electricity |
| Eth | Ethanol (E85) |
| CNG | Compressed Natural Gas |

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**TABLE 3** Transmission Type Categorization

| M | Non-automated manual transmissions |
|---|---|
| A | Automatic transmissions with more than one speed, includes shiftable automatic transmissions |
| AM | Automated manual transmissions (i.e. and dual clutch transmissions) including shiftable automated manual transmissions |
| CVT | Continuously variable transmissions, including selective continuously variable transmissions. |
| Null | Full Electric Vehicles |

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**TABLE 4** Drivetrain Layout Categorization

| | |
|---|---|
| 2WD | Front-Wheel Drive Systems, Rear-Wheel Drive Systems |
| 4WD | 4-Wheel Drive Systems, All-Wheel Drive Systems, Part-Time 4-Wheel Drive Systems |

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To fully describe and categorize a vehicle's powertrain, additional joining categories are defined for both the drivetrain layout and the vehicle's degree of electrification as shown in Table 4 and Table 5.

The final step in defining a primary key is the classification of vehicle body designs. This enables the identification of vehicles that share common aerodynamic characteristics, as well as providing a means for identifying redesign events that involve either a change to the body-in-white vehicle structure (a major redesign), or a change in bolt-on and trim components (a minor redesign, or 'refresh'.)

Lineage ID serves as an identifier of vehicles that are related over multiple model years. Lineages are defined from a consumer's perspective, and in most cases correspond to individual model names. A single Lineage ID can be applied to different trims levels (e.g. SE, LE) and different body styles (e.g. 2-door, 4-door.) In cases where a manufacturer introduces a vehicle that is simply renamed or clearly descended from a vehicle with a different model name, a common Lineage ID allows trends in vehicle characteristics to be followed from year-to-year.

**TABLE 5** Electrification Type Categorization

| N | All vehicles with no hybridization or electrification |
|---|---|
| HEV | All strong hybrid electric vehicles |
| REEV | All range-extended electric vehicles |
| EV | All electric vehicles with no range extension |

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Cabin ID is used to distinguish between vehicle body-in-white (BiW) structures, such as between a coupe and sedan variant of the same model. A Cabin ID remains constant over the lifespan of a particular structure, and only changes in the model year when the BiW is redesigned. Minor redesigns and 'refreshes' which involve only changes to trim and bolt-on components would not result in a change to the Cabin ID.

Body ID is used to define unique exterior designs. Different vehicle trim levels with unique Body ID's may utilize a common Cabin ID, but unique BiW structures will never share a common Body ID. Changes to a bolt-on and trim parts such as the hood, front fenders, door trim, grille, front fascia, etc. will result in a change in Body ID.

Of these three quantities, Body ID has the highest resolution, with one or more Body ID's associated with a single combination of Cabin ID and Lineage ID. For this reason, Body ID is employed as a joining field to represent a given vehicle model and trim.

**Data Querying and Aggregation Method** Once each data source has been properly formatted and primary keys assigned, the vehicle specification data can be queried and aggregated. The results of the desired data query are provided as the maximum, minimum, weighted average, or most frequently recurring value (in the case of non-numeric data), as well as values bounded by the maximum and minimum values of a separate category. In this study, average quantities were weighted using the production volumes from EPA VERIFY allocated to reflect assignments based on CAFE Footprint and sub-configuration and evenly distributed over appropriately matching entries in the master index file. For vehicles with multiple fuels, volumes were only allocated to entries using the vehicle's primary fuel source.

The aggregating fields used here were the combination of the CalcID (the Model Type level used for GHG compliance), fuel usage and Body ID. This combination was chosen to correspond to the level of resolution used in EPA's GHG compliance analysis.

Examples of the data aggregation process are shown below, with Table 6 showing an example of the master index file with joining fields and equivalent test weight (ETW) data field, while Table 7 and Table 8 show aggregations of the data by Calc ID alone and on Body ID alone respectively. Another query involving data from an outside source is shown below as well, with Table 9 showing the source file, Table 10 showing the joined master index file and source file and Table 11 showing a query on a combination of Calc ID and Body ID.

# Methodology for Calculating Key Characteristics

## Road Load Force and Tractive Energy Intensity

Road load force ($F_{road\ load}$) is the total resistive force acting on a vehicle, and can be calculated as a function of velocity and coast down test coefficients as shown in Equation 1 .

$$F_{roadload}(v) = A + Bv + Cv^2 \quad (1)$$

**TABLE 6** Master Index File Example

| Master File Index | Calc ID | Body ID | RLHP | Prod. Vol. | ETW | Trns Type | Fuel Type | Drive System |
|---|---|---|---|---|---|---|---|---|
| 1 | 10000 | 10 | 10 | 100 | 3500 | A | G | 2WD |
| 2 | 10000 | 10 | 10.1 | 300 | 3500 | M | G | 2WD |
| 3 | 10000 | 10 | 10.2 | 250 | 3750 | A | G | 4WD |
| 4 | 10000 | 11 | 10 | 350 | 4000 | A | G | 2WD |

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**TABLE 7** Aggregation of Data from Master Index File on Calc ID

| Calc ID | Production Volume | ETW Max | ETW Min | ETW Avg | ETW Max RLHP | ETW Min RLHP |
|---|---|---|---|---|---|---|
| 10000 | 1000 | 4000 | 3500 | 3738 | 3750 | 3500 |

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**TABLE 8** Aggregation of Data from Master Index File on Body ID

| Body ID | Production Volume | ETW Max | ETW Min | ETW Avg | ETW Max RLHP | ETW Min RLHP |
|---|---|---|---|---|---|---|
| 10 | 650 | 3750 | 3500 | 3596 | 3750 | 3500 |
| 11 | 350 | 4000 | 4000 | 4000 | 4000 | 4000 |

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**TABLE 9** Source File Example

| Source File Index | Curb Weight | Body ID | Trns Type | Fuel Type | Drive System |
|---|---|---|---|---|---|
| 1 | 3515 | 10 | M | G | 2WD |
| 2 | 3736 | 10 | M | G | 4WD |
| 3 | 3449 | 10 | A | G | 2WD |
| 4 | 3454 | 10 | A | G | 2WD |

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Where $A$, $B$ and $C$ represent the road load coefficients in lbf, lbf/mph and lbf/mph$^2$ respectively.

The total road load force is the result of aerodynamic drag, as well as tire, brake, hub, driveshaft, and transmission neutral drag forces. Conceptually, these can be represented broadly as aero and non-aero drag forces that are both a function of speed, as shown Equation 2.

$$F_{roadload}(v) = F_{aero}(v) + F_{non-aero}(v) \tag{2}$$

Tractive energy ($E_{tractive}$) is the energy that is required to propel a vehicle over the test cycle, and is a primary determinant of fuel consumption. The value can be determined by evaluating each time increment of the drive cycle by comparing the incremental inertial energy $dE_{inertia}$ and road load energy $dE_{road\ load}$ [3]. If the sum of the incremental road load energy and inertial energy are positive over an increment, the vehicle is assumed to be propelling itself, and the resulting tractive energy over the time increment is added to the overall tractive energy of the cycle. This can occur when the vehicle is accelerating, and also when undergoing moderate deceleration. At higher rates of deceleration, if the reduction in inertial energy exceeds the road load energy, the vehicle is assumed to be braking. The resulting negative difference in energies then represents the braking energy, and there is no contribution to total tractive energy over the time increment. This relationship between road load energy, inertial energy, and tractive energy is described by Equation 3. Equations 4 and 5 describe the calculation of incremental inertial and road load energy respectively. Tractive energy intensity is calculated using the sum of the tractive energy over the drive cycle and averaged over the entire distance covered over the cycle ($d_{cycle}$), which was obtaining by performing integral analysis over the drive cycle.

$$E_{tractive} = \sum_{0}^{t_{cycle}} dE_{tractive} = \sum_{0}^{t_{cycle}} \left(dE_{inertial} + dE_{roadload}\right), \quad dE_{inertial} + dE_{roadload} \geq 0 \tag{3}$$

$$dE_{inertial}(t) = m_{ETW} \frac{dv_{cycle}}{dt}(t) * dt \tag{4}$$

$$dE_{roadload}(t) = \left(A + Bv_{cycle}(t) + Cv_{cycle}(t)^2\right) * dt \tag{5}$$

## Powertrain Efficiency and Fuel Energy Intensity

As described in EPA's 2016 Technical Support Document for the Proposed Determination [2], powertrain efficiency $\eta_{peff}$ is a useful metric for evaluating trends in emissions-reducing technologies across the entire fleet, and over multiple years, without requiring 1-D full vehicle simulations for each individual vehicle. For a particular drive cycle, powertrain efficiency can be defined as the ratio of the tractive energy propelling the vehicle to the fuel energy expended [3]. This definition is equivalent to the ratios of energy intensity $\dot{E}$ (energy per unit of distance traveled); thus:

$$\eta_{peff} = \frac{\dot{E}_{tractive}}{\dot{E}_{fuel}} \tag{6}$$

The fuel energy intensity over a given drive cycle can be calculated using the fuel economy obtained for the cycle $MPG_i$ and the volumetric energy content of the fuel $\overline{HV}$, as shown in Equation 7. Combined cycle powertrain efficiency is defined as the weighted average of 55 percent city, 45 percent highway drive cycles. As such, fuel energy intensity can be calculated using the harmonically averaged fuel economy between the city and highway drive cycles. Tractive energy intensity for the combined cycle can be calculated using a weighted average

**TABLE 10** Joined Master Index File with Source File

| Master File Index | Calc ID | Body ID | RLHP | Production Volume | Curb Weight |
|---|---|---|---|---|---|
| 1 | 10000 | 10 | 10 | 100 | 3449 |
| 1 | 10000 | 10 | 10 | 100 | 3454 |
| 2 | 10000 | 10 | 10.1 | 300 | 3515 |
| 3 | 10000 | 10 | 10.2 | 250 | NaN |
| 4 | 10000 | 11 | 10 | 350 | NaN |

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**TABLE 11** Data Query for Source File Data on Calc ID and Body ID

| Calc ID | Body ID | Production Volume | Curb Weight Max | Curb Weight Min | Curb Weight Avg | Curb Weight Max RLHP | Curb Weight Min RLHP |
|---|---|---|---|---|---|---|---|
| 10000 | 10 | 650 | 3515 | 3449 | 3490 | 3515 | 3449 |
| 10000 | 11 | 350 | NaN | NaN | NaN | NaN | NaN |

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of city and highway tractive energy intensity, as shown in Equation 8.

$$\dot{E}_{fuel,i} = \frac{\overline{HV}}{MPG_i} \tag{7}$$

$$\dot{E}_{tractive,comb} = 0.55 * \dot{E}_{tractive,city} + 0.45 * \dot{E}_{tractive,hwy} \tag{8}$$

## Aerodynamic Drag Force

The aerodynamic drag force acting on a vehicle $F_{aero}$ for a given can be defined as a function of air density ($\rho_{air} = 1.17 \text{kg/m}^3$), velocity ($v$) and drag area ($C_D A_f$) as shown in Equation 9.

$$F_{aero}(v) = \frac{1}{2} \rho_{air} C_D A_f v^2 \tag{9}$$

In order to estimate drag area for a broad range of vehicles, we assume that non-aerodynamic drag forces make no contribution to the B coefficient [2]. Then, by Equation 9 and differentiation of Equation 1, drag area can be estimated by:

$$C_D A_f \approx \frac{B + 2Cv_{aero}}{\rho_{air} v_{aero}} \tag{10}$$

This approximation requires the choice of a velocity, $v_{aero}$, to use for the calculation of drag area. Here, we determined that a value of $v_{aero}$ = 45mph will minimize RMS error over the combined city and highway test cycles. Once the drag area is determined, the coefficient of drag, $C_D$, can be determined by normalization with a vehicle's frontal area, $A_f$. Frontal area can be approximated using Equation 11 based on a vehicle's overall width ($W_{veh}$), height ( $H_{veh}$ ), track width ($T_{veh}$), tire width ($W_{tire}$), and ground clearance $GC_{veh}$.

$$A_f \approx W_{veh} H_{veh} - \left(T_{veh} - W_{tire}\right) GC_{veh} \tag{11}$$

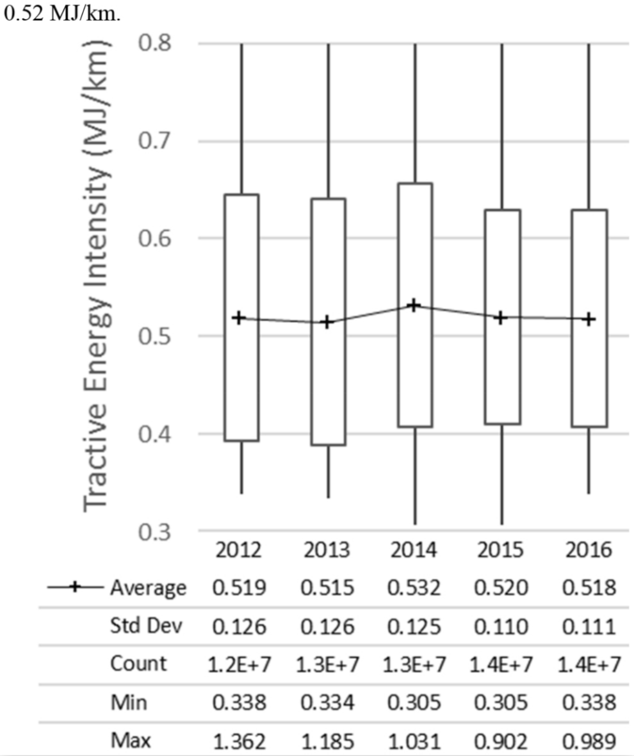
# Summary of Key Vehicle and Technology Characteristics for MYs 2012-2016 Fleets

## Tractive Energy Intensity

Reductions in tractive energy, whether by reducing the vehicle mass or by reducing aerodynamic and non-aerodynamic drag forces, can be a potentially effective strategy for reducing vehicle emissions. As shown in Figure 5, while the distribution of tractive energies has tightened somewhat from MYs 2012 to 2016 (±1σ from 0.252 MJ/km to 0.222 MJ/km), the overall fleet average has not changed notably during that time, with the sales-weighted average remaining around 0.52 MJ/km.

The trend in tractive energies are shown separately for car and truck regulatory fleets in Figure 6. While the car fleet has remained relatively constant at approximately 0.45 MJ/km, the truck fleet has experienced a 7 percent reduction in tractive energy, from 0.66 MJ/km in MY2012 to 0.61 MJ/km in MY2016. This reduction for trucks is masked in the overall fleet average shown in Figure 5 by the shift in market share during that time from cars to trucks.

**FIGURE 5** Five-year trend of tractive energy intensity for non-electrified vehicles, U.S. light-duty fleet



| | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Average | 0.519 | 0.515 | 0.532 | 0.520 | 0.518 |
| Std Dev | 0.126 | 0.126 | 0.125 | 0.110 | 0.111 |
| Count | 1.2E+7 | 1.3E+7 | 1.3E+7 | 1.4E+7 | 1.4E+7 |
| Min | 0.338 | 0.334 | 0.305 | 0.305 | 0.338 |
| Max | 1.362 | 1.185 | 1.031 | 0.902 | 0.989 |

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**FIGURE 6** Five-year trend of tractive energy intensity for non-electrified vehicles, U.S. car fleet (blue) and truck fleet (red)

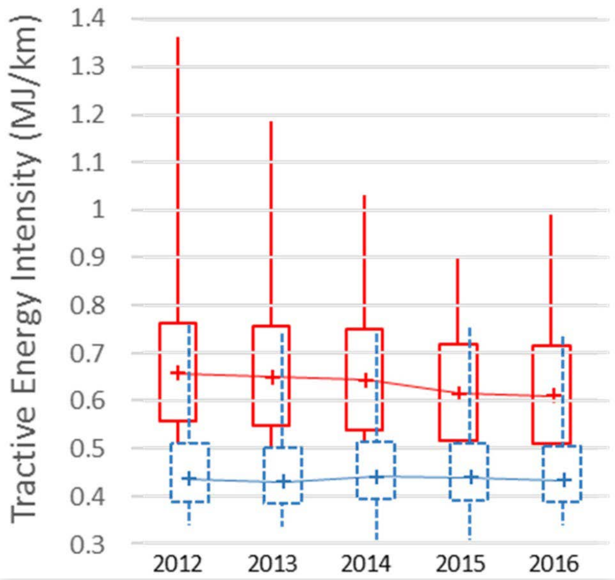

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**FIGURE 7** Distribution of powertrain efficiencies, Five-year trend, gasoline powertrains, U.S. light-duty fleet

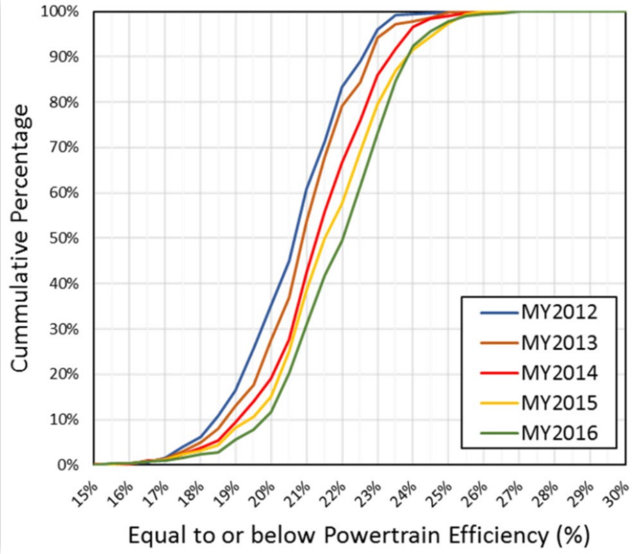

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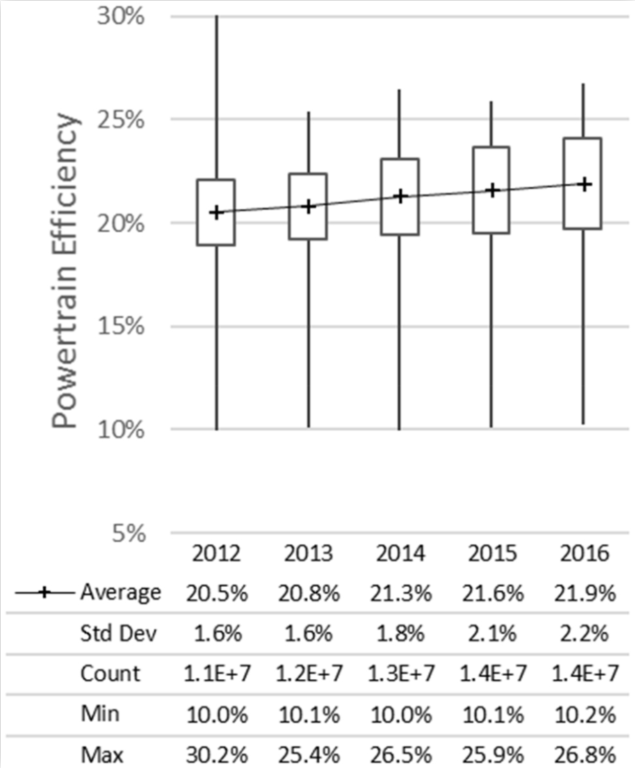
**FIGURE 8** Five-year trend of powertrain efficiency, gasoline powertrains, U.S. light-duty fleet



| | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Average | 20.5% | 20.8% | 21.3% | 21.6% | 21.9% |
| Std Dev | 1.6% | 1.6% | 1.8% | 2.1% | 2.2% |
| Count | 1.1E+7 | 1.2E+7 | 1.3E+7 | 1.4E+7 | 1.4E+7 |
| Min | 10.0% | 10.1% | 10.0% | 10.1% | 10.2% |
| Max | 30.2% | 25.4% | 26.5% | 25.9% | 26.8% |

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## Powertrain Efficiency

Figure 7 shows the distribution of powertrain efficiencies for non-electrified gasoline vehicles over the five model years from 2012 to 2016. The continual annual improvement seen in this figure is quantified in Figure 8, with average powertrain efficiencies increasing from 20.5 percent in MY2012 to 21.9 percent in MY2016.

## Aerodynamic Characteristics

As described earlier, we assembled a database for use in characterizing the baseline fleet, based in part on an identifier for the vehicle body. For this analysis of aerodynamic characteristics, we assumed that vehicles sharing the same body (i.e. Body ID) will have the same $C_D$ value. This assumption, aside from being grounded in a physical justification, enables the assignment of aerodynamic drag coefficients to entries lacking information on either vehicle measurements or road load coefficients.

Because there are often multiple vehicle configurations that share a common body, the estimated $C_D$ values might vary as an artifact of the road load coefficients depending on the applicability of the assumptions inherent in Equation 10 to a particular vehicle. In order to minimize this effect, a $C_D$ value was assigned considering a vehicle chosen to represent the lowest non-aero drag force configuration among all configurations with the same body. The priority of criteria used to select the lowest non-aero road load configuration is shown in Table 12.

The trends in drag coefficients are shown in Figure 9 for sedans. In the five model years considered from 2012 to 2016, sedans have improved only modestly, from an average of $C_D$=0.31 in MY2012 to $C_D$=0.30 in MY2016. When considering only the vehicles that had undergone major redesigns in the model year, defined as changes in the vehicle structure (i.e. body-in-white), the averages are $C_D$=0.30 in MY2012 and $C_D$=0.29 in MY2016.

Figure 10 shows trends in coefficient of drag values for CUV/SUV body styles. In contrast to sedans, $C_D$ trends for CUVs and SUVs are somewhat more pronounced over these five years, with

**TABLE 12** Prioritization of Estimated CD Values per Body ID

| Ranking Priority | Ranking Description |
|---|---|
| 1 | 2-Wheel Drive, Front or Rear |
| 2 | Non-Manual Transmission (does not include automated manual transmissions) |
| 3 | Minimum road load horsepower calculated from road load coefficients, used only if multiple vehicles tie within the first two rankings |

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**FIGURE 9** Five-year trend of Sedan aerodynamic performance ($C_D$) in the U.S. for entire light-duty fleet (left) and major redesigns (right)

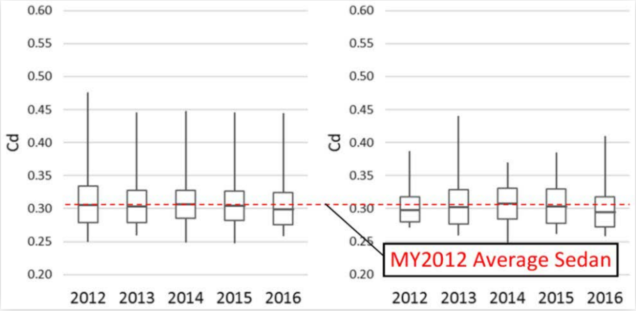

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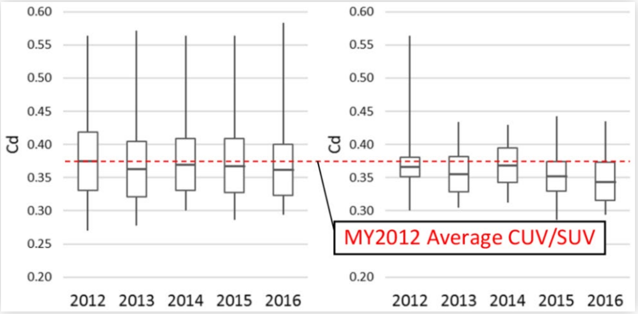
**FIGURE 10** Five-year trend of CUV/SUV aerodynamic performance ($C_d$) in the U.S. for entire light-duty fleet (left) and major redesigns (right)



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average values of $C_D$=0.38 in MY2012 and $C_D$=0.36 in MY2016. Similarly, vehicles that had undergone major redesigns in the model year saw average improvements from $C_D$=0.37 in MY2012 to $C_D$=0.34 in MY2016, indicating that as new designs are introduced, they will tend to drive the overall averages down.

## Baseline Fleet Technology Assignments Using ALPHA Full-Vehicle Simulation

The Advanced Light-Duty Powertrain and Hybrid Analysis (ALPHA) tool was created by EPA to evaluate effectiveness of technology packages for reducing GHG emissions. Benchmarking data from existing production vehicles as well as developmental vehicles and combustion models have been used to calibrate the ALPHA model for the purpose of producing $CO_2$ effectiveness estimates for various possible technology combinations, in vehicles with varying operating load and performance characteristics. Here, we introduce a methodology for using full-vehicle simulations to appropriately characterize technologies of current vehicles, and provide an illustration using the MY2016 fleet. This characterization of the baseline fleet is intended to provide a consistent basis from which to evaluate the $CO_2$ improvement potential in future fleets. This process for using ALPHA simulations to represent future technologies is discussed further in a companion paper [5].

As shown earlier in Figure 3 and Figure 4, there may be significant variation in $CO_2$ performance among various implementations of a given nominal technology. The procedure used for assigning the appropriate technologies to the baseline fleet is as follows:

1) Assemble the data set of fleet specifications, as described earlier.
2) Generate the initial technology assignments based on the nominal technology descriptions. This includes engine maps, transmission models, drive system type (FWD, RWD, AWD, 4WD), stop-start (with and without), and electric power steering (with and without) and the associated accessory loads. See Table 13 and Table 14.
3) Run ALPHA simulations for each vehicle in the fleet using the initial technology assignments and the actual road load coefficients and test weight.
4) Review the modeled $CO_2$ results, and the correlation with actual CO2 certification values for each vehicle.
5) In cases where either the city cycle, highway cycle, or combined $CO_2$ deviates significantly from the modeled value to the actual value, determine whether the initial technology assignment was appropriate, and whether there is justification to apply a different level within the same nominal technology (e.g. technologies such as a second generation turbocharged engine, a second generation 6-speed transmission, or improved accessories, which may be difficult to discern solely from the technology descriptions available in the data set.)
6) In cases where, for a given nominal technology model (e.g. a first generation six-speed transmission in a rear-wheel drive application) the sales-weighted average $CO_2$ of all modeled applications deviates from the average of certification $CO_2$ values, the ALPHA representation may not be appropriate. In such cases, the development of a new ALPHA engine map, transmission model, etc. may be justified.
7) Iterate Steps 5 and 6 above until the modeled $CO_2$ of the entire fleet lies within an acceptable range.

The results of the process described above are summarized in Figure 11 and Figure 12 for all non-electrified gasoline powertrains in the MY2016 fleet. Overall, the average modeled fleet $CO_2$ is within 2 g/mi of the actual fleet $CO_2$, and the majority of modeled values are within ±10 g/mi of the certification values. While some individual vehicles exhibit

**TABLE 13** Engine maps used for MY2016 Fleet ALPHA runs

| OMEGA code | Engine Map Basis |
|---|---|
| PFI | MY2014 MalibuGDI minus GDI effect |
| PFI+DeacPD | ALPHA DeacPD adjustment to PFI |
| GDI | MY2014 Malibu GDI |
| | MY2014 4.3L Silverado w/o Deac |
| GDI+DeacPD | MY2014 4.3L Silverado |
| ATK2 | MY2014 SkyActiv 13:1 |
| TDS11 | MY2013 Ecoboost 1.6L |
| | MY2015 Ecoboost 2.7L |
| TDS12 | MY2016 MY Honda 1.5L |

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**TABLE 14** Transmission models used for MY2016 Fleet ALPHA runs

| OMEGA code | Transmission Model Basis |
|---|---|
| TRX11 | 6-speed GM (2014 MY) |
| TRX12 | 6-speed GM (with efficiency improvements and rapid warmup associated with 2020 MY) |
| TRX21 | 8-speed ZF (2014 MY) |
| TRX22 | 8-speed ZF (with efficiency improvements and rapid warmup associated with 2020 MY) |
| Null | 5-speed AT |

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**FIGURE 11** Correlation between certification tailpipe CO2 values and model ALPHA values for MY2016 non-electrified vehicles

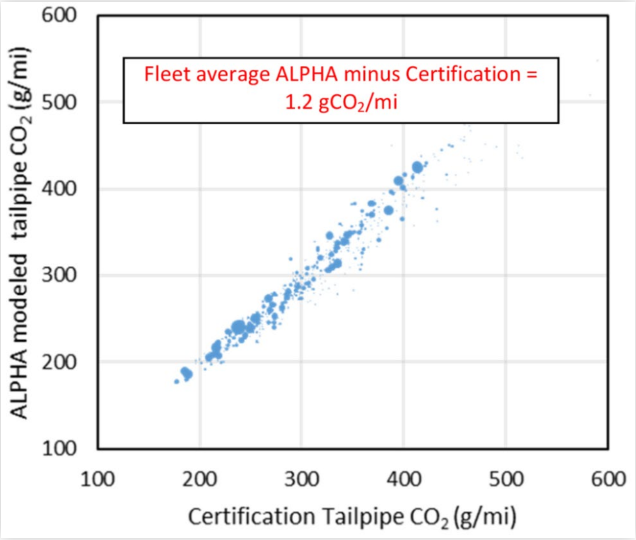

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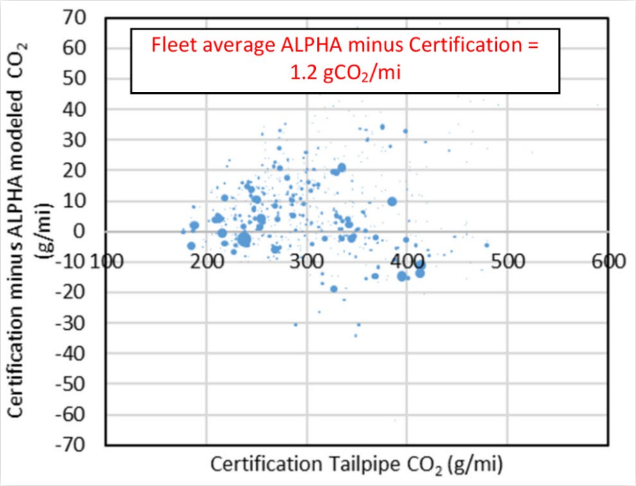
**FIGURE 12** Residual difference between certification tailpipe CO2 values and model ALPHA values for MY2016 non-electrified vehicles



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deviations of more than 20 g/mi, it is important to note that in EPA's compliance analysis, these modeled values are used for the purpose of generated incremental $CO_2$ effectiveness values of future fleet technology packages, and are not used directly in EPA's compliance analyses [5]. So, for example, if a discrepancy is due to anomalies in the reported road load coefficients, the application of an incremental, percentage reduction in $CO_2$ for a future technology package would still produce a reliable absolute estimate for the future $CO_2$ value that is needed in the compliance analysis. Nevertheless, EPA will continue to investigate the remaining differences between modeled and actual $CO_2$, and if necessary reassign technologies or apply new technology models to particular vehicles in the effort to further improve the accuracy of the baseline fleet characterization.

# Summary/Conclusions

An evaluation of the feasibility of reducing GHG emissions of the current fleet using advanced technologies relies on an accurate characterization of the technologies that have already been applied to the fleet, including not only a notation of the vehicle characteristics and presence of physical hardware, but also a consideration of how a particular technology implementation influences the potential for further emissions reductions.

As part of the effort to continually improve future fleet GHG compliance modeling tools and be responsive to public comments regarding, EPA has studied ways to improve the approach used to estimate $CO_2$ effectiveness estimates the analysis supporting light-duty greenhouse gas standards. The expanded use of full vehicle simulation is a promising approach for producing an accurate characterization the baseline fleet $CO_2$ performance, as described in this paper, and for ensuring an appropriate basis from which to measure the potential for future $CO_2$ reductions - a topic discussed further in a companion paper [5]. The key conclusions in this paper are:

- There are often different levels of effectiveness for each technology implemented by manufacturers to meet GHG standards. For example, not all turbochargers have the same effectiveness, because some are more advanced than others depending on design improvements.
- To track effectiveness and cost for each technology added to the baseline fleet, full vehicle simulation modeling must be used to robustly characterize the effectiveness of both the baseline and future vehicle for every vehicle in the baseline fleet.
- EPA's ALPHA model now has the capability to run a large number of simulations to support characterization of the entire baseline fleet of approximately 1500 vehicles along with the progression of technologies toward a future fleet.
- EPA was able to successfully apply the ALPHA tool to robustly characterize the technology content in each vehicle in the baseline fleet. The modeling runs were also used as the starting point for a related paper which explores the use of ALPHA to characterize technologies in each vehicle in a future fleet.
- The updated modeling methodology described in this paper appears to be a promising expansion of the use of full vehicle simulation in EPA assessments of the effectiveness of various technologies to meet future GHG standards.

# References

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## Definitions/Abbreviations

**PFI** - Port fuel injection

**DeacPD** - Partial, discrete (PD) cylinder deactivation where a portion of all cylinders can be activated and deactivated after an interval of multiple firing events. (compare to full, continuous deactivation)

**GDI** - Gasoline direct injection

**ATK2** - High compression ratio Atkinson cycle engines

**TDS11** - First generation low boost (~18bar) turbocharged engines

**TDS12** - Section generation low boost (~18bar) turbocharged engines

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