# Decomposing Fuel Economy and Greenhouse Gas Regulatory Standards in the Energy Conversion Efficiency and Tractive Energy Domain

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## Abstract[1]

The three foundational elements that determine mobile source energy use and tailpipe carbon dioxide ($CO_2$) emissions are the tractive energy requirements of the vehicle, the energy conversion efficiency of the propulsion system, and the energy source. The tractive energy requirements are determined by the vehicle's mass, aerodynamic drag, tire rolling resistance, and parasitic drag. The energy conversion efficiency of the propulsion system is dictated by the tractive efficiency, non-tractive energy use, kinetic energy recovery, and parasitic losses. The energy source determines the mobile source $CO_2$ emissions. For current vehicles, tractive energy requirements and overall energy conversion efficiency are readily available from the decomposition of test data. For future applications, plausible levels of mass reduction, aerodynamic drag improvements, and tire rolling resistance can be transposed into the tractive energy domain. Similarly, by combining thermodynamic, mechanical efficiency, and kinetic energy recovery fundamentals with logical proxies, achievable levels of energy conversion efficiency can be established to allow for the evaluation of future powertrain requirements. Combining the plausible levels of tractive energy and efficiency provides a means to compute sustainable vehicle and propulsion system scenarios that can achieve future regulations. Using these principles, the regulations established in the United States (U.S.) for fuel consumption and $CO_2$ emissions are evaluated. Fleet-level scenarios are generated and compared to the technology deployment assumptions made during rule-making. When compared to the rule-making assumptions, the results indicate that a greater level of advanced vehicle and propulsion system technology deployment will be required to achieve the model year (MY) 2025 U.S. standards for fuel economy and $CO_2$ emissions.

## Introduction

To understand the characteristics and limitations of vehicles in regard to energy use and dissipation it is useful to analyze vehicles and fleets in the energy conversion efficiency and tractive energy domain. This method can reveal quantitative understanding of vehicles, vehicle technologies and opportunities for research and development in ways that are less clear or even obscured by only evaluating the more common fuel economy, fuel consumption, and tailpipe $CO_2$ emissions domain.

Studies of vehicle energy requirements and dissipation have been well described by Sovran [1,2], Sovran and Blazer [3,4] and others [5-11]. A restatement of vehicle physics, largely from Thomas [8] follows, which is the basis for characterizing vehicles in the energy conversion efficiency and tractive energy domain for the specific purposes of this study and was utilized for previous efforts [7-10]. The specific development given is useful for analysis of vehicle chassis dynamometer test data available from vehicle certification applications and other sources [12]. For this application, no consideration of elevation change, vehicle lateral movement, or ambient conditions (such as wind) are needed.

### *Fuel/Electrical Energy*

Liquid and gaseous fuels have different energy densities and compositions which are of obvious importance and must be considered in detail. However, for additionally examining vehicle performance in the energy conversion efficiency and tractive energy domain, fuel economy and tailpipe $CO_2$ emissions must first be converted from their native units into a common energy-based metric.

This work is meant to enhance quantitative understanding of compliance implications for the National Highway Traffic Safety Administration (NHTSA) and the U.S. Environmental Protection Agency (EPA) joint final rules concerning Corporate Average Fuel Economy (CAFE) and greenhouse gas (GHG) emissions for model years 2017 through 2025 passenger cars and light trucks [13]. The vehicle testing basis of these regulations is the U.S. EPA two-cycle or combined-cycle unadjusted fuel consumption used both for NHTSA CAFE and EPA $CO_2$ emissions regulations [13,14]. This combined cycle scheme consists of 55% city cycle and 45% highway cycle combined on a distance driven basis. Accordingly, this regulatory fuel consumption is calculated using Equation 1.

$$FC_{c\&h} = 0.55 \cdot FC_{city} + 0.45 \cdot FC_{hwy} \qquad (1)$$

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This 55%/45% city/highway drive cycle combined calculation will be used throughout this paper unless otherwise explicitly stated.

The combined-cycle fuel consumption $FC_{c\&h}$ can be expressed in units such as gallons/mile, MJ/km, other energy/distance units, or translated to $CO_2$ grams per unit distance (the regulations are in g/mi $CO_2$ and mpg for fuel economy). The terms $FC_{city}$ and $FC_{hwy}$ are the unadjusted (sometimes referred to as "raw") values calculated from performing the FTP (Federal Test Procedure, city cycle) and HWFET (Highway Fuel Economy Test) tests. By regulation, GHG and CAFE test procedures currently specify ethanol-free certification gasoline to be used for fuel economy determination, and certification fuel economy values are based on Tier 2 or similar certification fuel, not the ~10% ethanol fuel (Tier 3 and in-use fuels) which contains roughly 3% lower volumetric heating value. Assuming that GHG/CAFE compliance determination will remain based on 0% ethanol (E0) fuel or that appropriate test procedure adjustments will be made to maintain parity with performance on E0 fuel, all comparisons in this paper are made on the basis of E0 performance. The EPA estimates one U.S. gallon of E0 gasoline produces 8887 grams of $CO_2$ based on 100% gasoline fuel, and similarly, 10180 grams $CO_2$ per gallon of diesel fuel [15].

## *Tractive Energy*

A vehicle driven on the road, or on a chassis dynamometer experiences forces in the driving (horizontal) direction and these forces determine (actual or simulated) vehicle motion. The vehicle powertrain supplies tractive drive force to the wheels, $\mathbf{F_{tr}}$, and the braking system supplies force opposite the driving direction, $\mathbf{F_b}$. The composite drag force, $\mathbf{F_d}$, (rolling resistance, aerodynamic drag and other friction resistance) opposing the motion of the vehicle at any velocity $\mathbf{V}$, is often modeled by the quadratic equation

$$\mathbf{F_d = A + BV + CV^2} \quad (2),$$

for vehicle testing purposes. The composite drag force, $\mathbf{F_d}$, is also sometimes referred to as road load. Equation 2 is determined by coastdown testing techniques described in SAE International Standard J2263 [16] and the coefficients are unique to each vehicle model. Multiple sources provide the coefficients needed for Equation 2 with the most data rich source being the U.S. EPA Verify queries [12]. Other valid methods of producing a drag force equation can be used for certain purposes including modeling applications.

The force balance equation for a vehicle can be expressed as (driving direction is positive)

$$\sum \mathbf{F = Ma = F_{tr} - F_b - F_d} \quad (3).$$

The powertrain tractive force, $F_{tr}$, is considered only for positive values and the action is at the tires (which are on the dynamometer roller drums or the road). When the tractive force is negative during a deceleration, this negative force is assumed to be supplied by vehicle and powertrain braking ($\mathbf{F_b}$). The inertial term **Ma** is vehicle mass (**M**) times acceleration (**a**).

It is useful to consider the possible applications of the above equation during a chassis dynamometer vehicle test. Three cases to consider follow.

<u>Vehicle acceleration</u>. $\mathbf{F_{tr} = F_d + Ma}$, with the **Ma** term adding to the required powertrain-supplied tractive force. For constant speed $\mathbf{F_{tr} = F_d}$.

<u>Vehicle deceleration with no braking required</u>. Then $\mathbf{F_{tr} = F_d + Ma}$, with the **Ma** term subtracting from the required powertrain-supplied tractive force.

<u>Vehicle deceleration with braking</u>. The powertrain provides no positive tractive force and braking must augment the drag force to adequately decelerate the vehicle. $\mathbf{F_{tr} = 0}$, $\mathbf{F_b = Ma - F_d}$.

Application of the above development allows quantification of energy use and energy dissipation over standard test cycles. Forces can be integrated over distance to obtain energy requirements throughout the cycles using $\int \mathbf{F \cdot ds}$ (energy = force x distance), where **F** is a force and **ds** is an increment of distance. This technique allows calculation of the powertrain-provided tractive energy, $\int \mathbf{F_{tr} \cdot ds = E_{tr}}$, for a defined drive cycle including the portions of tractive energy needed to overcome drag losses, $\mathbf{E_d}$, and braking losses, $\mathbf{E_b}$. In summary these drive cycle energy quantities are calculated by

$$\int \mathbf{F_{tr} \cdot ds = E_{tr}}, \quad \int \mathbf{F_d \cdot ds = E_d}, \text{ and } \quad \int \mathbf{F_b \cdot ds = E_b}.$$

Furthermore, it can be shown that these quantities are related as in Equation 4 (provided the drive cycle begins and ends with the vehicle stopped and there is no elevation change) [1,2,8].

$$\mathbf{E_{tr} = E_d + E_b} \quad (4)$$

The EPA Test Car List Data Files [12] provides the unadjusted fuel economy values for vehicles tested over cycles which allows the amount of fuel energy used during a test, $\mathbf{E_{fuel}}$, to be calculated. Also provided by the database are each vehicle's test weight known as the equivalent test weight (ETW) which is used to represent vehicle mass (including rotating mass), **M**, and the **A**, **B** and **C** road load force coefficients mentioned previously.

## *Energy Conversion Efficiency*

For this study, the vehicle specific fuel energy conversion efficiency $\boldsymbol{\eta_{tr}}$ is defined as the ratio of (powertrain provided) tractive energy required to move the vehicle over a drive cycle, $\mathbf{E_{tr}}$, to the fuel or electrical energy consumed over that cycle, $\mathbf{E_{fuel}}$. as given by Equation 5. The term tractive efficiency will be used throughout this study.

$$\boldsymbol{\eta_{tr}} = \mathbf{E_{tr} / E_{fuel}}, \quad (5)$$

Equation 5 provides a measure of the full vehicle's ability to use fuel to power the vehicle motion and any needed accessories for the specific drive cycle and test conditions and is occasionally referred to as tank-to-wheels efficiency. This efficiency is relatively simple to calculate for internal combustion engine (ICE) powertrains, including the case of ICE-electric hybrid powertrains, provided the cycles examined are completed with zero net charging/discharging of the vehicle batteries (experimentally obtaining the correct gasoline consumption over cycles is more difficult for HEVs and involves obtaining larger amount of data and perhaps use of corrections for battery state of charge variations).

In some form Equation 5 can be applied to all road vehicles. It becomes more difficult practically and conceptually for vehicles which use two separate fuels. Battery electric vehicles (BEV) need some further consideration due to significant dissipation of the electrical energy when charging (grid-to-wheels) and because the efficiency values can exceed 100%, which perplexes some and begs for explanation. The case of the electric vehicle is reviewed in the Appendix using data for a Nissan Leaf to assist in this explanation.

## Energy Conversion Analysis

### *Efficiency Variation with Powertrain and Vehicle Type*

Figure 1 provides the fuel energy as a function of tractive energy requirements for MY 2016 vehicles over the city and highway test cycles (55% FTP/45% HWFET). The data are binned by powertrain type for spark ignition (SI), compression ignition (CI), SI-electric hybrids, and battery electric. Lines of constant efficiency are provided as a reference. For MY 2016, the production-weighted average tractive efficiency is estimated to be over 22% for the combined fleet. The current best SI-based non-hybrid powertrains provide energy conversion efficiencies of just less than 26%. The best CI-based non-hybrid powertrains provide tractive efficiency levels of up to 29%; 12% better than comparable SI powertrains. The efficiency of SI-electric hybrids depends upon the architecture, with mild hybrids providing between 25% and 27% efficiency, while P2 hybrids offer efficiencies up to 30%. Parallel-series hybrids offer the highest performance with tractive efficiencies of up to 40%. Current battery electric powertrains have tractive efficiencies ranging from 82% to 93%, including battery charging losses.

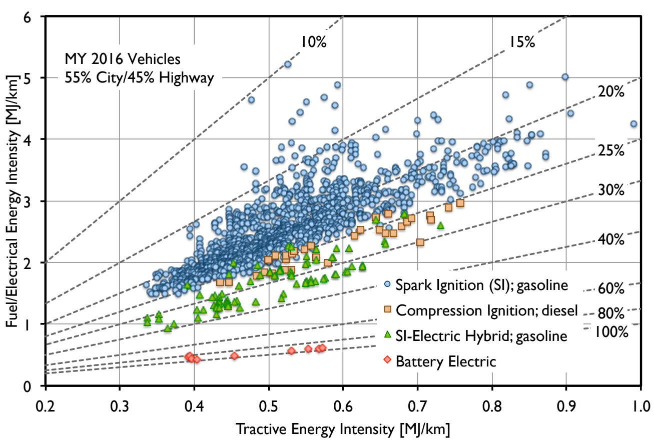


Figure 1. Fuel energy as a function of tractive energy; MY 2016 light duty vehicles.

A primary benefit of assessing vehicle performance in the efficiency domain is that efficiency is relatively neutral to vehicle type. For a given drive cycle and powertrain type, the first order determinant of efficiency is the relative operating load. For internal combustion engines, this load is typically reported as the brake mean effective pressure (BMEP) but, more simply, it is the ratio of average operating load to the engine displacement. Specific fuel consumption as a function of displacement normalized load, for spark-ignition powertrains, is shown in Figure 2 for MY 2016 light duty vehicles (again over the city and highway test cycles, 55% FTP/45% HWFET). Lines of constant tractive efficiency are provided as reference. As shown, assuming similar relative loads, the vehicle type is inconsequential to tractive efficiency.

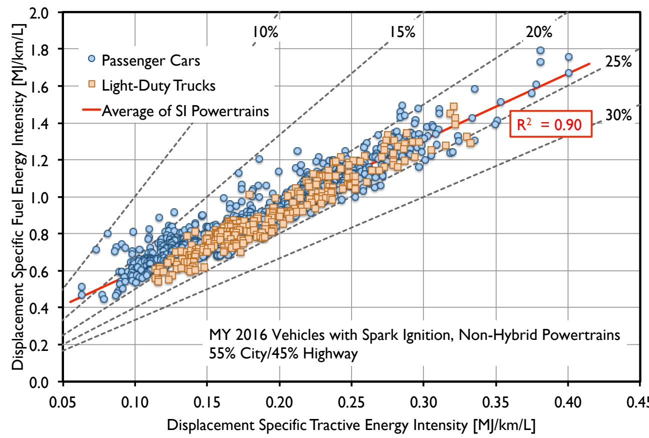


Figure 2. Displacement specific fuel energy vs. displacement specific tractive energy; MY 2016 light duty vehicles.

As shown by the trend line, engine displacement and vehicle tractive energy accounts for 90% ($R^2 = 0.90$) of the variation in fuel consumption among the 1241 spark ignition powered light-duty vehicle tests evaluated. The same concepts exist for electric motors and drivetrain components. The trend line illustrates how changes in average load per unit engine displacement affects efficiency. Due to friction and parasitic losses, efficiency degrades as specific load drops. For SI-based powertrains, the efficiency trend (red line) ranges from less than 15% at less than 0.10 MJ/km/L to nearly 25% at 0.40 MJ/km/L, representing a greater than 60% change.

Another key benefit of conducting assessments in the efficiency domain, rather than the fuel consumption or the tailpipe $CO_2$ domain, is that plausible upper limits can be established from thermodynamic and mechanical principles. As shown in Figure 1, the best on-cycle tractive efficiency values for SI-based vehicles are approaching 26%, which is significantly lower than more commonly reported peak engine efficiencies which are typically between 30 and 38% for spark ignition engines. For any power source (e.g., ICE, electric motor) the tractive efficiency will always be lower than the maximum efficiency of the power source due to the on-cycle losses, which include:

1. Not operating at peak component efficiencies (engine, motors, transmissions) due to vehicle speed and load requirements
2. Non-tractive fuel/electrical use (coasting, idling, and utility loads)
3. Mechanical losses (e.g., transmission) with higher losses during warm-up
4. Control system constraints (e.g., driveability, tailpipe and evaporative emissions control, on-board diagnostics, noise-vibration-harshness)

### *Efficiency Variation with Drive Cycle*

While these principles can be applied to all drive cycles, the tractive efficiency is dependent upon typical loads, the amount of idle, the amount of coasting, accessory loading (e.g., air conditioning) and test conditions, such as ambient and start-temperature. As stated earlier, increasing load generally improves the efficiency of engines, transmissions, and electric motors. For any given vehicle, high speed, high acceleration drive cycles such as the EPA US06 have higher tractive energy intensity, which will result in higher on-cycle efficiencies. Conversely, increasing engine idling time can degrade efficiency as there is no tractive work. Due to friction and control system requirements for driveability and emissions, efficiency is always lower during cold operation, such as the cold FTP test (EPA Cold CO), and warm-up. The Cold CO test is the same three phase drive cycle as the FTP, but conducted at -7 °C (20 °F) ambient instead of 24 °C (75 °F). Similarly, adding accessory loads will reduce efficiencies. For example, the EPA SC03 drive cycle includes air conditioning loads under hot ambient conditions.

As a reference, tractive efficiency as a function of drive cycle is provided in Figure 3 for a mid-sized cross-over utility vehicle. The influence of warm-up (FTP Bag 1 versus FTP Bag 3), colder ambient temperature (Cold CO Total versus FTP Total), increased tractive load (US06 Highway versus HWFET), and air conditioning loads (SC03 versus FTP Bag 3 Total) on tractive efficiency is clear from these test results.

Tractive efficiency will be lower for the new European Drive Cycle (NEDC) as this cycle has considerably more non-tractive events (coasting and idle) that don't contribute to tractive work.

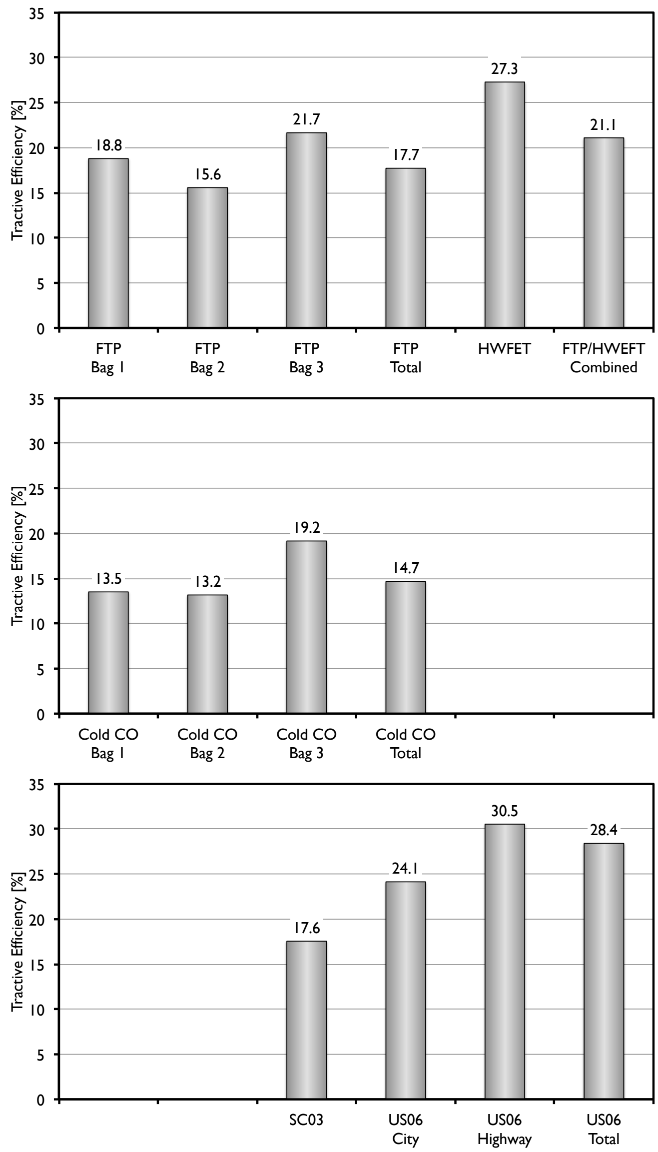


Figure 3. Tractive efficiency as a function of various drive cycles for a mid-sized cross-over utility vehicle.

## *Energy Conversion Trends and U.S. Market Progression*

The U.S. light-duty market has been dominated by conventional gasoline powertrains, with ICE-electric hybrid sales generally staying near 3% of the market, varying from 2.2% to 3.9 % since MY 2007. Alternative powertrain vehicles including plug-in ICE-electric hybrids, electric vehicles, and compressed natural gas (CNG) fueled vehicles have represented no more than 0.7% of the market while diesel fueled vehicles have had roughly 1% market share.

Some important changes in deployed powertrain technology for the U.S. market from MYs 2005 to 2015 are summarized in Figure 4. Key powertrain technologies shown include variable valve timing (VVT), gasoline direct fuel injection (GDI), turbocharging, cylinder deactivation, SI-electric hybrids, engine stop-start, transmissions with greater than 5 step ratios, and non-hybrid continuously variable transmission (CVT). Perhaps the largest contribution to propulsion efficiency improvement has been a nearly complete turnover of automatic transmissions from 4 and 5 step ratios to greater than 6 step ratios as well as a significant deployment of CVTs.

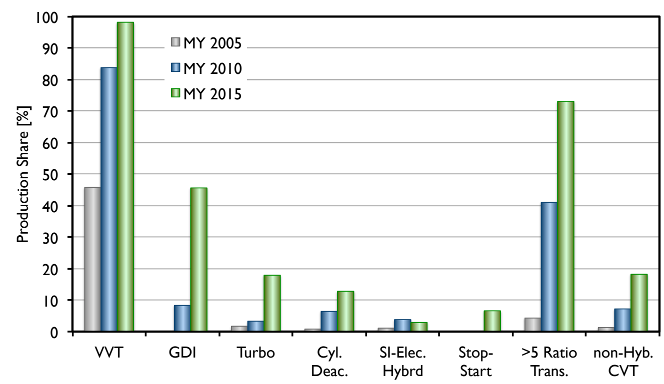


Figure 4. Powertrain technology market penetration for selected MYs [14]

Evaluation of the tractive efficiency of the U.S. passenger car and light-duty truck fleets over the same 10-year period is presented in Figure 5. The entire ensemble production-weighted fleet is represented for each model year.

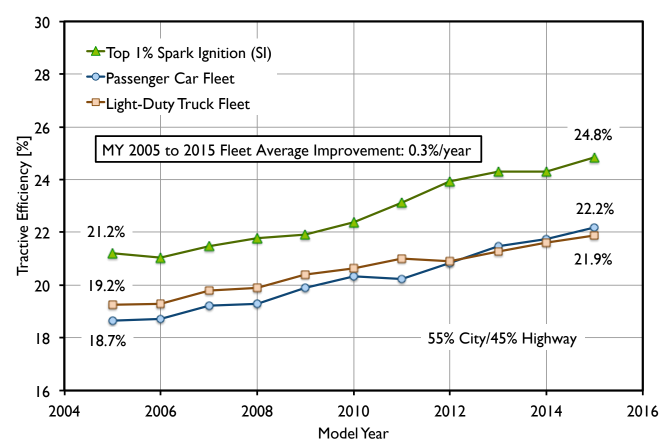


Figure 5. Tractive efficiency vs. model year

From MY 2005 to MY 2015, the fleet average efficiency increased from approximately 19% to 22%, a 16% improvement. Through this 10-year period, the efficiency increased fairly linearly, by 0.3% per year, despite the non-linear deployment of powertrain technology.

As shown, vehicle type (cars versus trucks) is not a strong predictor of on-cycle efficiency and as also shown earlier in Figure 2; trucks can be as efficient as passenger cars. Also shown in Figure 5 is the trend for the best 1% of SI-based powertrains. For MY 2005, the best 1% achieved an efficiency level of 21.2% or better. Even with the rapid deployment of new powertrain technologies, the fleet average efficiency did not reach this level until MY 2013, an eight-year period.

In a previous study [8], 40 U.S. light-duty gasoline same-model MY 2005 and MY 2015 vehicles (one ICE-electric hybrid included) were chosen carefully to match the attributes of the entire 2014 fleet [14]. Matched attributes included fleet fuel economy, proportions of vehicle types, average ETW, average engine peak power and displacement, proportions of transmission types and four-wheel drive vehicles, and fraction of GDI fueled engines. For this 10-year period a 16.4% relative efficiency improvement was found over the regulatory cycles. The vehicles also revealed improvements in required tractive energy, with this value dropping 5.6% over the 10 years. This study is in general agreement with the results provided in Figure 5.

The vehicle efficiency and tractive effort domain analysis is useful for understanding individual vehicle model progress. Using the Honda Civic as an example in Figure 6 and 7 (data points highlighted as blue circles, with Figure 6 giving a "panoramic" view with other MY 2016 vehicles in gray), it is seen that fuel energy intensity often improves significantly with successive model introductions with tractive energy intensity decreasing more modestly. However, the successive models increase in size as indicated by vehicle footprint and mass increasing roughly 9% from 2005 to 2016, therefore vehicle tractive energy improvements would be incrementally greater had vehicle size and mass remained static. Relatively large efficiency improvements are seen from the 5 speed transmission being replaced by a CVT for MY 2015 and then subsequently for the turbocharged and downsized engine model introduced for MY 2016. These metrics were generated using EPA test car database regulatory cycle results [12].

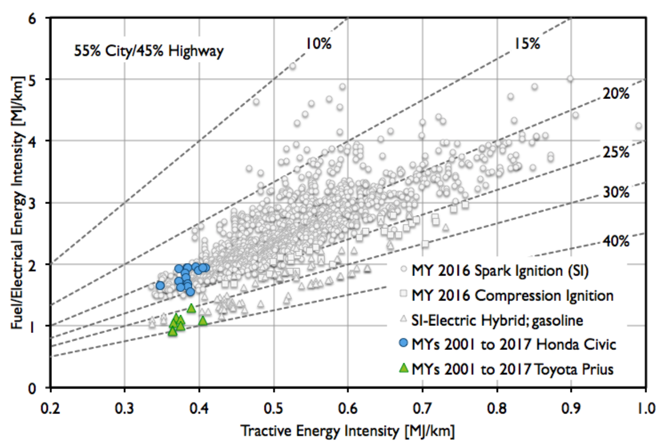


Figure 6. Model year 2016 light-duty vehicles are shown in the fuel energy tractive energy intensity domain. Successive Honda Civic and Toyota Prius models from MY 2001-MY 2017 are also included.

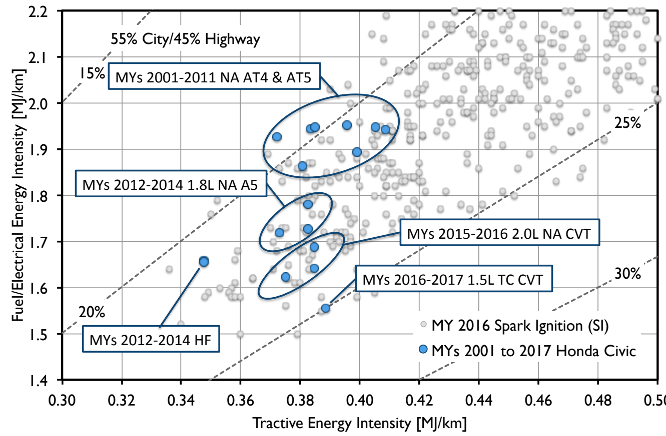


Figure 7. Successive Honda Civic models show progression in fuel energy and tractive energy intensity. NA = naturally aspirated; TC = turbocharged; AT = automatic transmission, HF = Civic model designation

A trend that this type of analysis reveals is that as a vehicle's tractive effort requirement are lowered (due to reduced mass, friction, etc.) with the powertrain unchanged, the tractive efficiency decreases, at least slightly. The reason is the improved vehicle operates at a reduced load during the cycle (see the trend line in Figure 2). In Figure 7 the Civic HF is likely an example of this effect. Fuel and tractive energy intensity is lower for the HF model compared to the other 2012-2014 Civic models, and indeed the on-cycle efficiency is slightly lower as well.

Examining the successive generations of the Toyota Prius is given as a second example, again via use of the EPA test car database regulatory cycle results. In Figure 8 (green triangles, also shown in Figure 6) it is seen how Toyota has improved the powertrain efficiency from 30% to 38% since the initial introduction of the Prius in MY 2001, and further reaches to nearly 40% efficiency with the Prius Eco. Various changes in tractive energy are seen with successive models, with a relatively large 7% change observed by comparing the 2001-2003 Prius to the 2016-2017 Prius Eco.

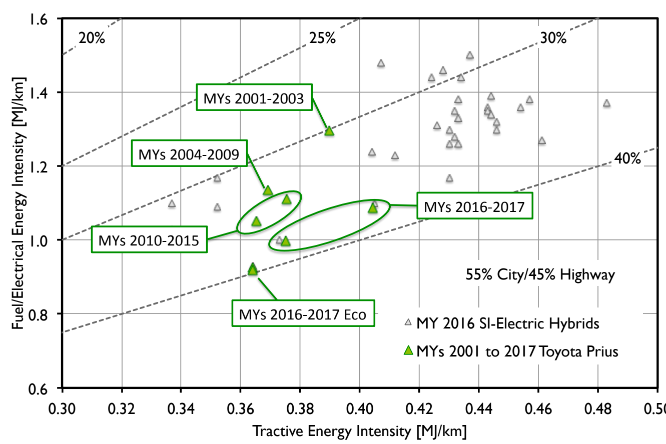


Figure 8. Successive Toyota Prius models show progression in fuel energy and tractive energy intensity.

While the best production non-hybrid SI engines achieve peak efficiencies exceeding 37% [17] (with corresponding on-cycle efficiencies of 25%), future SI-based powertrains are being developed to deliver efficiencies that rival CI-based powertrains, which approach 42% [18] and in some non-U.S. markets have reached 44% [19]. Numerous studies have been performed on diesel engines with gasoline-based fuels with the objective of combining SI and CI technologies to achieve diesel-like efficiencies while reducing the emissions associated with conventional diesel fueled CI engines [20,21,22]. Additionally, some hybrid-specific SI engines have already demonstrated engine efficiencies exceeding 40% [23], however, these engines are designed to operate within a very narrow window in terms of engine speed, peak power and peak torque due to the advantages of coupling with an electric motor, as supported by Yamada, Adachi, et al. [24]. When all of these factors are considered, it is reasonable to expect these increasing efficiency trends to continue as technologies converge to deliver peak efficiency gains while also achieving all other requirements for a production engine in terms of engine control, U.S. market emissions, on-board diagnostic compliance and drivability.

## Decomposition Methodology

Global regulatory standards for light vehicles are presented in the fuel economy, fuel consumption, $CO_2$, or energy intensity domain. This is necessary as the goals of these standards are to reduce overall energy use and GHG emissions. However, to understand the on-cycle efficiency requirements of future powertrains, a decomposition of the regulatory standards is necessary. By applying the principles discussed in the previous sections, regulatory standards can be transposed into the on-cycle tractive efficiency and tractive energy domain, allowing plausible powertrain and vehicle attribute scenarios to be developed. For the purposes of this analysis, the U.S. GHG and CAFE standards were evaluated, although the process can be applied to any standard and drive cycle.

### *Fuel/Electrical Energy*

To determine on-cycle energy requirements, the EPA and NHTSA (the agencies) regulatory credit assumptions were subtracted from the projected achieved values [13]. This is necessary because EPA and NHTSA established various credit provisions as part of the standards programs, and future model year compliance projections include the impact of projected credit usage. These credits include the GHG benefits of improved air conditioning systems as well as technologies which improve the overall GHG signature of vehicles but are not adequately apparent and measured on the official city/highway test cycles (known also as "off-cycle" technologies, which generate "off-cycle" credits). Credits also include the incentives for alternative fuel capable automobiles (most commonly known as "flexible fuel vehicle" credits) as well as tradable/transferrable credits for exceeding average fuel economy standards, provided by Congress as part of the CAFE program [25,26].

Care is taken to separate these elements and account for the impact of regulatory program credits that are embedded in the EPA's projected GHG performance and NHTSA's projected CAFE performance. This assures that only the actual vehicle level $CO_2$ emissions and fuel economy levels are analyzed and the on-cycle energy requirements compared on an equal basis across vehicle categories and classes.

With the impact of credits removed, Figure 9 contains the agency projections for unadjusted 2-cycle combined fuel economy as a function of model year. Projections for passenger car and light truck fleets are assessed separately. The MY 2008 actuals are shown as these were used as the baseline fleets for the rulemaking. The EPA $CO_2$ emissions projections were converted to fuel economy values assuming 8887 grams of $CO_2$ per gallon of gasoline, which is the common conversion factor between fuel economy (in mpg units) and $CO_2$ emissions (in grams per mile units) jointly established by both agencies in a recent fuel economy standards rulemaking [27,15].

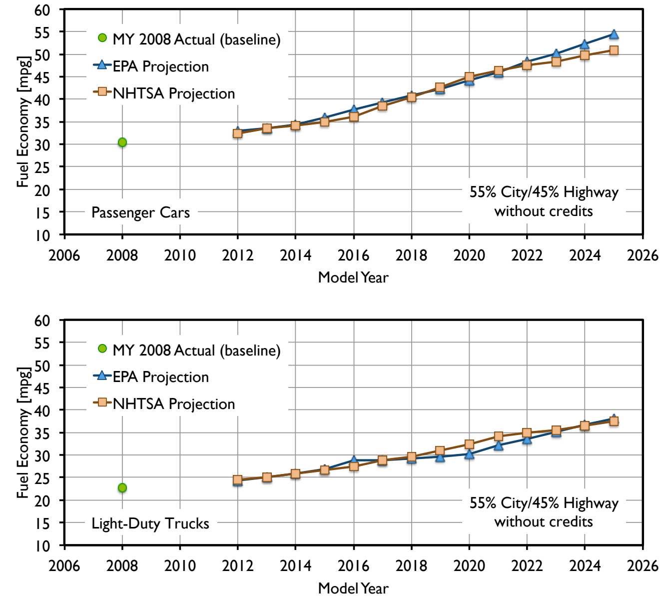

Figure 9. EPA and NHTSA 2-cycle (FTP/HWFET) fuel economy projections.

The actual 2-cycle fuel economy values are ultimately dependent upon the passenger car and light truck shares, the sales weighted footprint of each fleet, and the credits applied. Consequently, the actual fuel economy and tailpipe $CO_2$ emission requirements will likely differ from the projected values. However, for this analysis, the assumptions from the EPA and NHTSA were applied.

The projected achieved fuel economy was transposed into the fuel energy intensity domain using a fuel energy volume density of 32.1 MJ/L. The resulting data are shown for passenger cars and light trucks in Figure 10. From MY 2008 to MY 2025, the nearly linear reduction in fuel energy intensity is projected to be an average of 40.7% or 2.4% reduction per year.

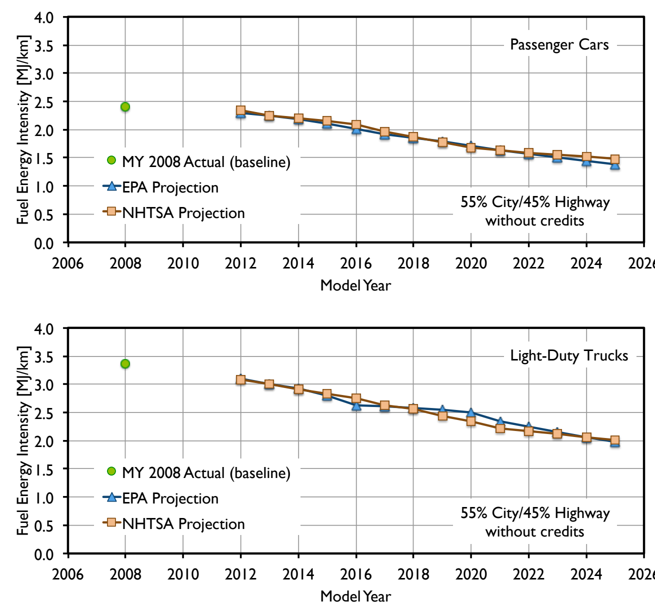

Figure 10. EPA and NHTSA 2-cycle (FTP/HWFET) fuel economy projections converted to the energy intensity domain.

### *Tractive Energy*

Evaluating tractive energy reductions is more involved since this attribute was not reported by the agencies. Rather, the agencies reported assumed reductions of the tractive energy elements of mass, aerodynamic drag and tire rolling resistance, relative to a baseline fleet. Both agencies used the MY 2008 fleet as a baseline and, therefore, the MY 2008 fleet was also used for this analysis as a direct comparison.

The baseline tractive energy was generated from the equivalent test weight (ETW) and road load coefficients from the MY 2008 EPA test car data files [12]. To obtain production-weighted tractive energy for each fleet, the production volume was mapped to the tractive energy for each vehicle. Production volumes were obtained from NHTSA [28]. Where required, the vehicle passenger car or light truck designation was changed from the MY 2008 designation to reflect updated vehicle classifications of passenger cars and light trucks beginning with the 2011 model year [14].

In order to assess the future state of the passenger car and light truck fleet as assumed by the agencies resulting from manufacturer improvements to the tractive energy attributes of mass, aerodynamic drag, and tire rolling resistance, the agency pathways relative to improvements in these attributes were catalogued from the rulemaking documents. The resulting reductions, for the MY 2008 baseline fleet, are presented in Table 1 for the years assessed during the rule making (2016, 2021, 2025).

Table 1. Assumed changes from the MY 2008 baseline fleet in tractive effort related vehicle attributes.

| Source | Model Year | Assumed Change in Attribute [%] | | | | | |
|---|---|---|---|---|---|---|---|
| | | Passenger Car | | | Light Truck | | |
| | | Mass | Aero. Drag | Tire RRC | Mass | Aero. Drag | Tire RRC |
| EPA | 2016 | -4.1 | -8.5 | -8.5 | -4.8 | -8.5 | -8.5 |
| | 2021 | -5.0 | -17.7 | -17.2 | -7.0 | -17.9 | -17.4 |
| | 2025 | -6.0 | -20.0 | -19.6 | -10.0 | -20.0 | -19.9 |
| NHTSA | 2016 | -2.7 | -7.6 | -6.6 | -4.3 | -9.9 | -6.5 |
| | 2021 | -3.8 | -16.5 | -13.9 | -8.3 | -17.3 | -13.9 |
| | 2025 | -4.4 | -16.5 | -15.0 | -11.5 | -17.8 | -15.6 |

In order to evaluate the effect of the agency assumptions for reduced vehicle mass, improved aerodynamics and reduced tire rolling resistance on tractive energy intensity, a full factorial analysis of each attribute was performed to cover the range of projected reductions and vehicle types. Five vehicle types were evaluated: a sedan, a passenger car based sport utility vehicle (SUV), a truck based SUV, a van, and a pickup truck. Starting with each baseline, vehicle mass, aerodynamic drag and tire rolling resistance were each modified using offsets of -20%, -15%, -10%, -3% and +5% for each parameter for a full factorial of combination of parameters. The results were then regressed to determine the change in tractive energy intensity with changes to each element.

Based on this analysis, a 10% reduction in vehicle mass will result, on average, in a 5.6% reduction in tractive energy intensity over the 55% FTP/45% HWFET combined cycle. Similarly, a 10% reduction in aerodynamic drag results in a 3.2% reduction in tractive energy intensity, while a 10% decrease in tire rolling resistance results in a 2.1% decrease in tractive energy intensity.

Applying these tractive energy reductions to the MY 2008 baseline results in the values in Table 2. These results are presented graphically in Figure 11. Based on this analysis, an average tractive energy reduction of 14%, from MYs 2008 to 2025, is implied from the agency assumptions for reductions of mass, aerodynamic drag, and tire rolling resistance. This represents an average reduction of approximately 0.8% per year. An independent study of tractive energy [10] suggested a technically plausible reduction of 10% from MY 2014 vehicles. While the approach of this study was different than the agency approach, the projections yield similar future tractive energy assumptions. Finally, the same principles outlined here can be used to assess alternate scenarios for mass, aerodynamic drag and tire rolling resistance reductions.

Table 2. Projected tractive energy requirements based on EPA and NHTSA assumptions for reductions in mass, aerodynamic drag, and tire rolling resistance.

| Source | Model Year | Tractive Energy [MJ/km] | |
|---|---|---|---|
| | | Passenger Car | Light-Duty Truck |
| Actual (baseline) | 2008 | 0.472 | 0.668 |
| EPA | 2016 | 0.439 | 0.620 |
| | 2021 | 0.414 | 0.579 |
| | 2025 | 0.406 | 0.560 |
| NHTSA | 2016 | 0.446 | 0.622 |
| | 2021 | 0.423 | 0.580 |
| | 2025 | 0.420 | 0.565 |

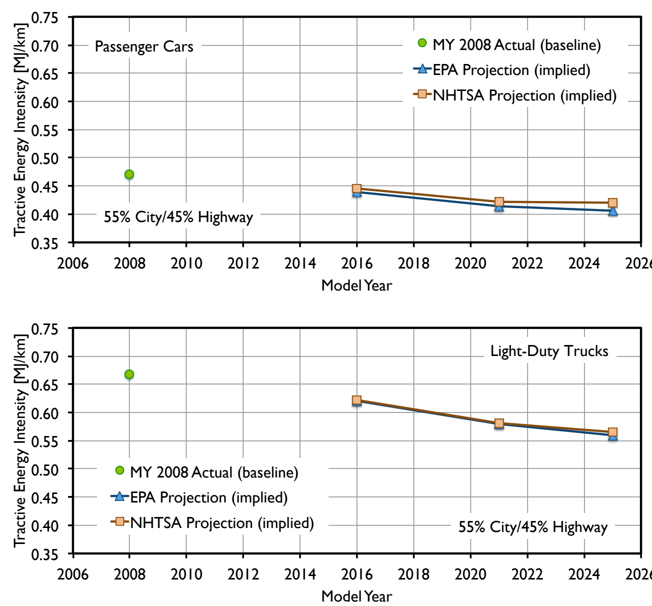


Figure 11. Implied tractive energy requirements based on EPA and NHTSA assumptions for reductions in mass, aerodynamic drag, and tire rolling resistance.

### *Energy Conversion Efficiency*

Combining the tractive energy intensity and fuel energy intensity projections provides energy conversion efficiency projections for MYs 2016 through 2025. A linear interpolation was assumed to generate assumptions for the model years not specifically assessed by the agencies. The resulting efficiencies, implied by the agency assumptions, are provided in Table 3 for MYs 2008, 2016, 2021, and

2025. Figure 12 provides the implied efficiencies for MYs 2016 through 2025 for passenger car and light-duty trucks with the actual MY 2008 fleets, which served as the agency baseline for the rule making.

Table 3. Implied 2-cycle (FTP/HWFET) efficiency based on EPA and NHTSA rule-making assumptions.

| Source | Model Year | Conversion Efficiency [%] | |
|---|---|---|---|
| | | Passenger Car | Light-Duty Truck |
| Actual (baseline) | 2008 | 19.3 | 19.9 |
| EPA | 2016 | 21.9 | 23.6 |
| | 2021 | 25.3 | 24.7 |
| | 2025 | 29.3 | 28.3 |
| NHTSA | 2016 | 21.4 | 22.7 |
| | 2021 | 26.0 | 26.2 |
| | 2025 | 28.3 | 28.1 |

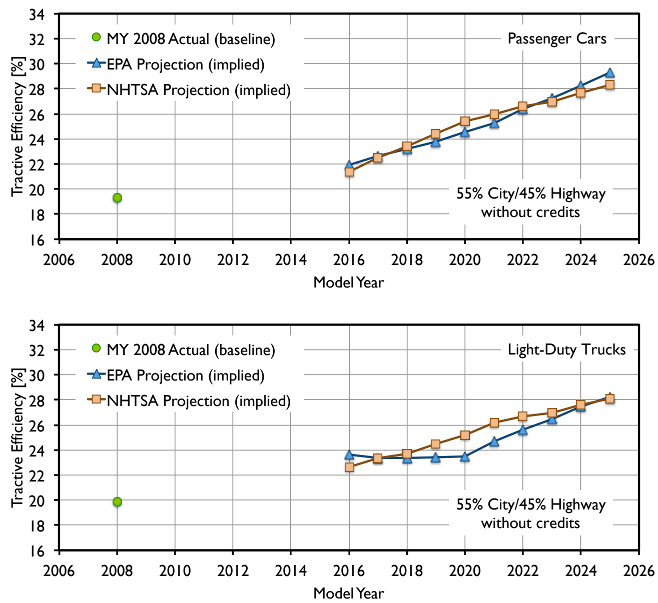


Figure 12. Implied 2-cycle (FTP/HWFET) tractive efficiency based on EPA and NHTSA rule-making assumptions.

While the trends between the agency projections differ, passenger car and light truck conversion efficiencies are required to rise by an average of 46% from MY 2008 to MY 2025, an average of 2.8% per year. Given the goal of harmonization, the tractive efficiency requirements implied by the standards should, ideally, be equal. However, since this is not the case, the required efficiencies will be the higher of the implied values for each fleet.

The historical tractive efficiencies (from Figure 5) and the highest implied efficiencies are shown in Figure 13 for each fleet. The solid lines represent the historical performance, while the dashed lines represent the implied requirements going forward. For reference, several MY 2016 powertrain technology bundles are provided. These include the highest efficiency (best 1%) spark ignition powertrains, compression ignition powertrains, and a range of full hybrids from parallel two clutch (P2) to parallel-series.

Several conclusions can be obtained from the results in Figure 13. First, for MYs 2016 through 2018, the efficiency requirements for light trucks are greater than the efficiency requirements for passenger cars. As stated earlier, efficiency is relatively independent of vehicle type and this result is the consequence of the process by which the standards were assembled. The effect of this is already apparent as trucks have been underperforming the standards for the past several years. Second, if the fleet average efficiency were raised to the best 1% MY 2016 spark ignition engines, the fleet would only achieve the standards through MY 2020. Similarly, if the spark ignition engines became, on average, as efficient as diesel engines, this would carry the fleet through to approximately MY 2023. Consequently, a spark-ignition dominated fleet is not a likely scenario for MY 2025.

Figure 14 provides the required progression of the passenger car and light-duty truck fleets from MY 2016 to MY 2025 in the energy and efficiency domain. As shown, the MY 2025 production-weighted passenger car fleet will need to achieve tractive energy and efficiency nearly equal to the first generation Toyota Prius (compare to Figure 8). The MY 2025 production-weighted light truck fleet will need to achieve tractive energy and efficiency levels similar to a MY 2016 mid-size sport utility vehicle with parallel SI-electric hybrid powertrain technology.

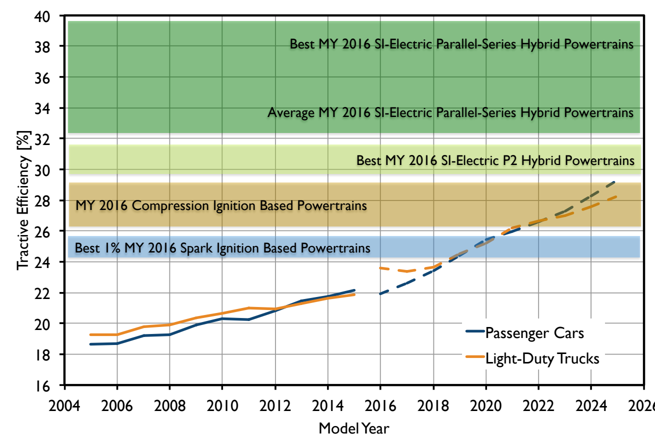


Figure 13. Historical fleet-level tractive efficiency and tractive efficiency requirements to meet the Agency regulations.

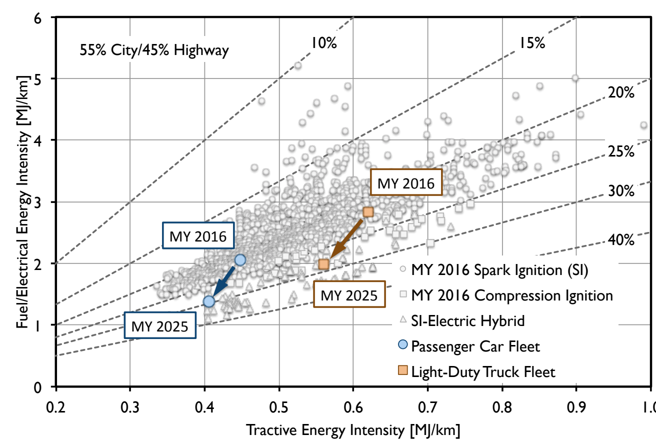


Figure 14. Future standards transposed into the energy and efficiency domain.

## Scenario Generation

To understand the U.S. market macro-level requirements for MY 2025 powertrains, scenarios can be generated based on efficiency assumptions and proxies. For purposes of this effort six basic powertrains were considered:

Improved Spark Ignition. The efficiency assumption for this powertrain is 25.1% and represents existing technologies (e.g., turbocharging and downsizing, Atkinson-cycle, high ratio spread transmissions, stop-start) that are combined, with learning, to move the average SI-based powertrain to the efficiency of the best 1% MY 2016 SI-based powertrains. Given the efficiency trends shown in Figure 5, this is not an unreasonable assumption assuming greater deployment of efficient SI powertrain technologies. The improved SI powertrain represents a 14% increase in efficiency relative to the average MY 2016 SI-based powertrain. Peak engine efficiencies in this scenario would be approximately 38%. Since this is an average, the assumption is that the best improved MY 2025 SI-based powertrains will exceed this level.

Advanced Spark Ignition. The efficiency assumption for this powertrain is 27.6% and represents concepts and technologies that currently do not exist in production and target CI-like efficiency assuming the limits of an SI-based powertrain (e.g., lower compression ratio yielding lower efficiency). Peak engine efficiencies in this scenario would approach 42% as noted earlier and supported by the efficiency targets of advanced SI development projects such as Southwest Research Institute's HEDGE-III [21,22] program. This represents a 10% improvement over the improved SI powertrains. As with the improved SI, this is an assumed average performance of the technology, consequently, the best advanced SI-based powertrains would exceed this efficiency value.

Improved Compression Ignition. The efficiency assumption for this powertrain is 29.8% and represents combinations of existing technologies (high ratio spread transmissions, stop-start) that, with learning, move the average CI-based powertrain to the best MY 2016 CI-based powertrain. As with the SI powertrain assumption, the best versions of this powertrain would exceed 29.8%.

Mild SI-Electric Hybrid. The efficiency assumption for this powertrain is 30% and represents the application of mild hybridization to the improved spark ignition powertrain.

Full SI-Electric Hybrid. The efficiency assumption for this powertrain is 37.6% and represents full hybrids learning to the best 1% of MY 2016 hybrid vehicles; a 10% improvement over the average MY 2016.

Electric. The efficiency assumption for this powertrain is 90% and represents on-cycle tractive efficiency of current battery electric vehicles.

Efficiency assumptions can be made more granular if desired for an alternative analysis. For example, instead of improved SI, the analysis can be conducted with specific SI-based technology bundles.

From these efficiency values, scenarios of powertrain mix rates that achieve the U.S. MY 2025 standards were generated by summing the on-cycle energy of each bundle and dividing by the total sales. Tailpipe $CO_2$ levels were computed by assuming 8887 grams of $CO_2$ per gallon for gasoline, 10180 grams $CO_2$ per gallon for diesel, and 0 grams $CO_2$ for battery electric vehicles. Three scenarios were generated to assess the level of electrification required to achieve the MY 2025 standards.

The first scenario (A) assumes CI, full SI-E hybrids, and electric vehicle shares are the same as MY 2016. The improved SI powertrain was assumed as the baseline powertrain and mild hybridization was added until the fuel consumption and tailpipe $CO_2$ emission levels equaled the MY 2025 requirements. In this scenario, the passenger car fleet requires 87% mild hybridization while the light-duty truck fleet requires 69% mild hybridization. This scenario is shown graphically in Figure 15.

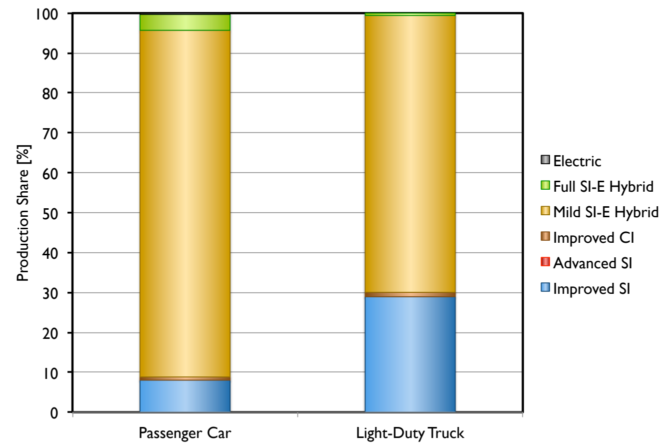


Figure 15. Scenario A; production share of mild hybridization and improved SI-based powertrains to achieve MY 2025 fuel consumption and tailpipe CO2 requirement.

The second scenario (B) assumes CI and electric vehicle shares are the same as MY 2016. The improved SI powertrain was assumed as the baseline powertrain and, instead of mild hybridization as in scenario A, full hybridization was added until the fuel consumption and tailpipe $CO_2$ emission levels equaled the MY 2025 requirements. In this scenario, the passenger car fleet requires 47% full hybridization while the light-duty truck fleet requires 35% full hybridization. This scenario is shown graphically in Figure 16.

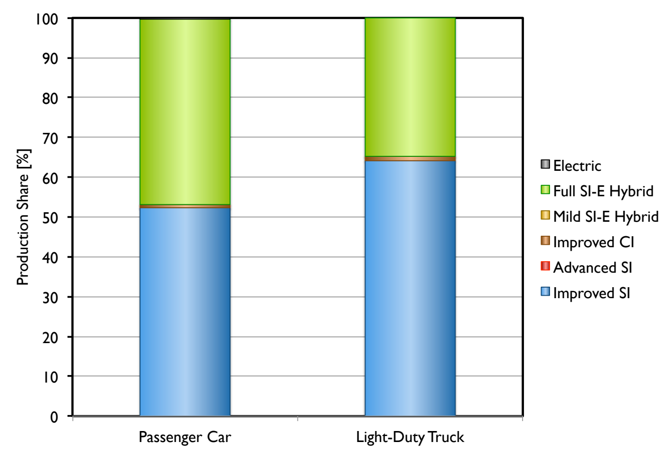


Figure 16. Scenario B; production share of full hybridization and improved SI-based powertrains to achieve MY 2025 fuel consumption and tailpipe CO2 requirement.

The third scenario (C) assumes CI and electric vehicle shares are the same as MY 2016. The advanced SI powertrain was assumed as the baseline powertrain and full hybridization was added until the fuel consumption and tailpipe $CO_2$ emission levels equaled the MY 2025 requirements. In this scenario, the passenger car fleet requires 28% full hybridization while the light-duty truck fleet requires 12% full hybridization. This scenario is shown graphically in Figure 17. This scenario is unlikely within the assessment timeframe (9 years) as it requires development and deployment, in high volumes, of SI-based powertrains that do not currently exist in the market.

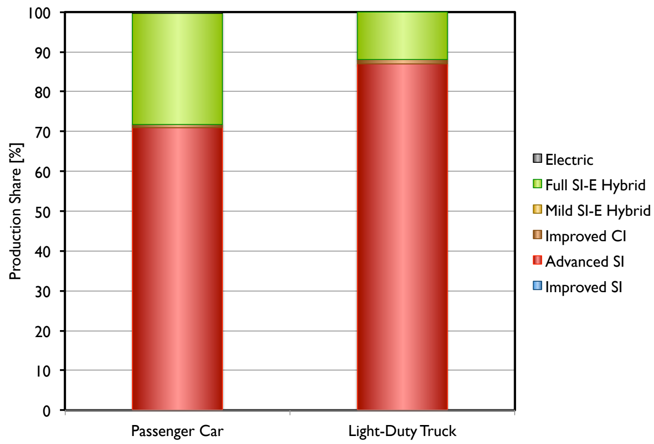

Figure 17. Scenario C; production share of full hybridization and advanced SI-based powertrains to achieve MY 2025 fuel consumption and tailpipe CO2 requirement.

The results of the three scenarios described are provided in Table 4. In each of these cases, the level of hybridization is significantly greater than the levels suggested by EPA and NHTSA evaluations [13]. Earlier agency studies [13] concluded that the MY 2025 standards could be achieved with mild and full hybridization production shares of 26% and 5%, respectively, with a foundation of SI-based powertrains that would be represented by our improved and advanced SI powertrains. A second EPA study [29] concluded that the MY 2025 standards could be achieved with a scenario that consisted of a foundation of SI powertrains that can be represented by improved and advanced SI, combined with 18% mild hybrids and with 5% full hybrids.

Table 4. Powertrain technology share for three compliant scenarios; tractive energy reductions assumed equivalent to EPA and NHTSA rule-making assumptions.

Passenger Car

| Powertrain Technology | Production Share [%] | | |
|---|---|---|---|
| | Scenario A | Scenario B | Scenario C |
| Improved SI | 8.0 | 52.3 | 0.0 |
| Advanced SI | 0.0 | 0.0 | 71.0 |
| Improved CI | 0.8 | 0.8 | 0.8 |
| Mild SI-E Hybrid | 86.9 | 0.0 | 0.0 |
| Full SI-E Hybrid | 4.0 | 46.6 | 27.9 |
| Electric | 0.3 | 0.3 | 0.3 |

Light-Duty Truck

| Powertrain Technology | Production Share [%] | | |
|---|---|---|---|
| | Scenario A | Scenario B | Scenario C |
| Improved SI | 28.9 | 64.1 | 0.0 |
| Advanced SI | 0.0 | 0.0 | 87.0 |
| Improved CI | 1.1 | 1.1 | 1.1 |
| Mild SI-E Hybrid | 69.4 | 0.0 | 0.0 |
| Full SI-E Hybrid | 0.6 | 34.8 | 11.9 |
| Electric | 0.0 | 0.0 | 0.0 |

## Regulatory Evaluations for Other Markets

The same energy and efficiency domain decomposition principles can be applied to light vehicle regulations in other markets such as the European Union, China, and Brazil.

One complication of evaluating the regulatory standards for these other markets in the energy conversion efficiency and tractive energy domain is availability of road load coefficients. Since the coefficients are not published for the vehicles in these markets, tractive energy must be estimated using the available test weight information combined with vehicle attributes (e.g., dimensions, body type, function) to generate estimates for aerodynamic drag, tire rolling resistance, and other vehicle losses.

## Summary/Conclusions

Decomposition of fuel economy and tailpipe $CO_2$ requirements into the tractive energy and efficiency domain provides a more holistic, yet first principles-based, assessment of the U.S. market regulatory standards to MY 2025.

By applying the principles, a macro-level assessment of technology bundles required to achieve the future U.S. fuel economy and greenhouse gas standards can be developed. This can provide manufacturers, regulators, and suppliers with a robust method of generating high-level, yet sustainable, scenarios that can achieve future standards.

The U.S. future standards cannot be achieved without higher levels of electrification than has been previously estimated by NHTSA and EPA. While the number of compliant scenarios is large, this analysis suggests that a mild-hybrid pathway will require that a majority of vehicles have the technology by MY 2025. Alternatively, a full-hybrid pathway suggests a market share of greater than 30%.

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## Definitions/Abbreviations

A First Target Coefficient

ARB Air Resources Board, California Environmental Protection Agency

B Second Target Coefficient

BEV Battery Electric Vehicle

C Third Target Coefficient

CAFE Corporate Average Fuel Economy

CI compression ignition

CVT continuously variable transmission

DOE U.S. Department of Energy

ds increment of distance for integration

$E_b$ cycle braking energy or work (kJ)

$E_d$ cycle drag energy or work (kJ)

$E_{fuel}$ energy in the fuel consumed during a given test cycle

$E_{tr}$ positive powertrain work that reaches the road (kJ) as tractive effort

EPA U.S. Environmental Protection Agency

ETW Equivalent Test Weight (usually reported in lbs)

F Force

FC Fuel consumption

$F_b$ braking force

$F_d$ drag force

$F_{tr}$ powertrain-supplied tractive force to the road

FTP Federal Test Procedure (U.S. regulatory city cycle)

GHG greenhouse gas

HEV hybrid electric vehicle

HWFET (U.S. regulatory) highway fuel economy test

ICE Internal combustion engine

Ma mass x acceleration

MY Model Year

NHTSA National Highway Traffic Safety Administration

ORNL Oak Ridge National Laboratory

SC03 Supplemental Federal Test Procedure drive cycle generally performed with the air conditioning system on and the test cell heated to 35 C.

SI spark ignition

SUV sport utility vehicle

US06 Supplemental Federal Test Procedure to simulate aggressive driving

V (vehicle) velocity

$\eta_{tr}$ Vehicle on-cycle efficiency, also referred to as tractive efficiency: fuel energy fraction reaching the road as tractive work

## Appendix. Examination of Battery Electric Vehicle (BEV) Efficiency Using Nissan Leaf Data

***Moving vehicles are always consuming or dissipating energy***

When a vehicle moves through a drive cycle, energy is always being dissipated. Friction and drag forces dissipate energy with the vehicle motion. Furthermore a practical vehicle has minor but real power use whenever it is turned on (dash lights, running lights, control units, etc.). Even for the case of a BEV going downhill and charging the battery with regenerative braking, the potential energy loss is greater than the battery energy gains due to dissipative electrical losses and drag forces. Aside from considering things like solar panels, vehicles driving through a cycle will continuously have net energy loss.

***Vehicle cycle conversion efficiency for an electric vehicle***

Vehicle fuel conversion efficiency is defined as the ratio of forward tractive energy required to move the vehicle over a drive cycle to the fuel energy consumed over that cycle. This is expressed by Equation 5, repeated below.

$$\boldsymbol{\eta_{tr} = E_{tr} / E_{fuel}} \quad (5)$$

When using this definition for electric vehicles, what some would consider unusually high $\boldsymbol{\eta_{tr}}$ values can occur and can actually exceed 100% for selected cycles. This simply means that over a drive cycle, the fuel energy used was less than the required forward tractive work to push the vehicle through the cycle. A value exceeding 100% only occurs when a relatively large amount of regenerative braking energy is captured and reused for tractive work over the cycle. Note that the inherent efficiency of the battery and electric motor drive train (battery-to-wheels) is generally in the 80-90% range [30,31].

### *Nissan Leaf UDDS cycle data analysis*

An illustration of high vehicle efficiency with experimental data is provided. Figure A.1 shows energy use and dissipation for the UDDS cycle from an ANL dynamometer test [31,32,33]. Energy from the "wall" or grid charges the battery and 16% of the energy is lost in the charging process (this is an assumption and was not measured). In Figure A.1 all efficiencies shown are based on the 6152 kJ of "wall" provided energy from the grid (grid-to-wheels based efficiency values). There are losses of 4% to parasitic loads and 18% drive system losses (again based on the 6152 kJ of grid energy used in charging). Although all losses (including charging loss) total 38%, the regenerative brakes capture and return energy to the battery and a net 32% is returned through the drive system to the road as tractive energy. Regenerative braking energy is 2602 kJ over the UDDS and a net 1960 kJ is captured and used to replenish the battery and subsequently used for tractive work [32,33]. The vehicle efficiency over the city cycle is approximately 94% (based on 5762 kJ / 6152 kJ), a very high value. Considering battery-to-wheels only, the vehicle-cycle efficiency becomes 112% (based on 5762 kJ / 5166 kJ).

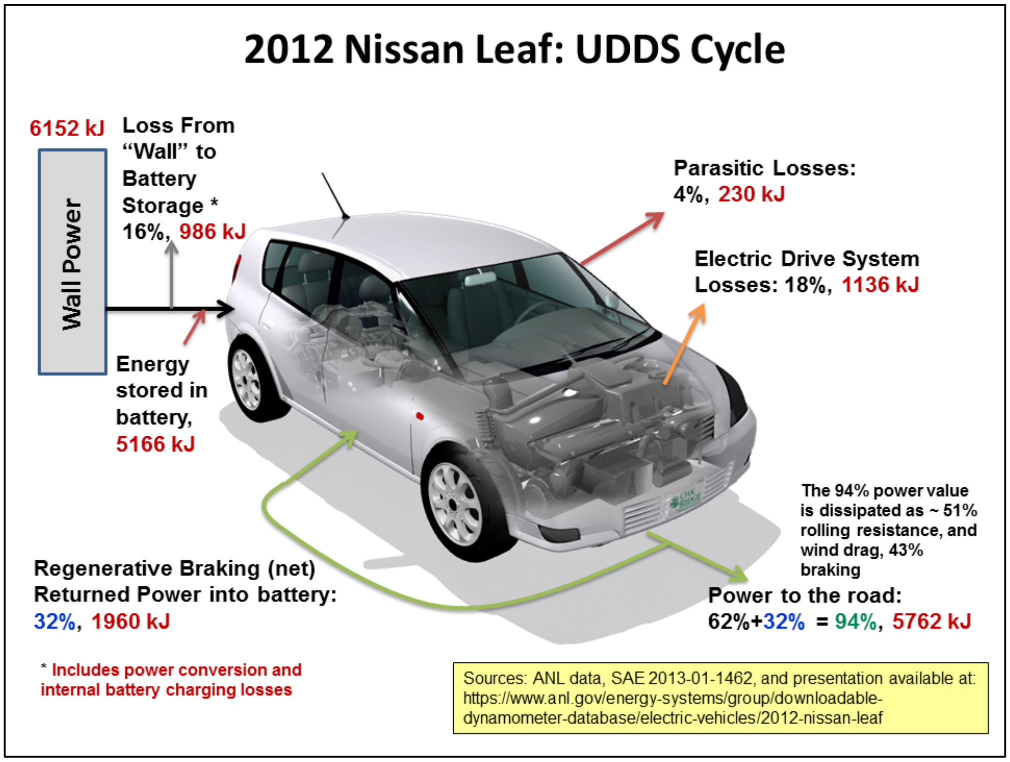


Figure A.1. Energy use and dissipation is given for a 2012 Nissan Leaf for the UDDS cycle. This Figure is modified from reference [7] and the test data is from ANL [32,33].

**End Notes**

A cycle could be chosen with a higher regenerative braking component that ensures the vehicle efficiency (grid-to-wheels) is over 100%. The grid-to-wheels method is valid considering that virtually no fuel is lost when adding liquid fuels to vehicles. Meaningful comparisons of efficiencies, emissions and further merits of electric vehicles to liquid and gas fueled vehicles requires extensive effort, such as well-to-wheels analysis or beyond.

Another efficiency metric has been formulated that will not result in efficiencies exceeding 100% for EVs and hybrids [6]. Consider the standard as a "perfect" idealized vehicle with regenerative braking and all braking energy is recovered. Using this as a standard, Equation 4 is recast as Equation 4' where only the net tractive effort after considering both the driving and braking directions is used to calculate efficiency as in Equation 5'. This equivalently means the "required" tractive effort is only that needed for overcoming drag forces.

$$\mathbf{E_{tr} = E_d + E_b} \quad (4)$$

$$\mathbf{E'_{tr} - E_b = E_d + E_b}\text{, or simply } \mathbf{E'_{tr} = E_d} \quad (4') \quad \text{and}$$

$$\boldsymbol{\eta'_{tr}} = \mathbf{E_d} / \mathbf{E_{fuel}}, \quad (5')$$

For the current application, the authors do not believe this alternative method will further illuminate the topic considered in this paper chiefly because the desire is to separately examine progress in vehicle cycle efficiency (which is essentially powertrain efficiency) and required cycle tractive effort.