

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

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ABSTRACT

The three foundational elements that determine mobile source energy use and tailpipe carbon dioxide (CO₂) 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 CO₂ 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 CO₂ 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 CO₂ emissions.

CITATION: Pannone, G., Betz, B., Reale, M., and Thomas, J., "Decomposing Fuel Economy and Greenhouse Gas Regulatory Standards in the Energy Conversion Efficiency and Tractive Energy Domain," *SAE Int. J. Fuels Lubr.* 10(1):2017, doi:10.4271/2017-01-0897.

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 CO₂ 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, 6, 7, 8, 9, 10, 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, 8, 9, 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 CO₂ 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 CO₂ 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.

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

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 CO₂ grams per unit distance (the regulations are in g/mi CO₂ 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 CO₂ based on 100% gasoline fuel, and similarly, 10180 grams CO₂ 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, F_{tr} , and the braking system supplies force opposite the driving direction, F_b . The composite drag force, F_d , (rolling resistance, aerodynamic drag and other friction resistance) opposing the motion of the vehicle at any velocity V , is often modeled by the quadratic equation

$$F_d = A + BV + CV^2 \quad (2)$$

for vehicle testing purposes. The composite drag force, 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)

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

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 (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.

Vehicle Acceleration

$F_{tr} = F_d + Ma$, with the Ma term adding to the required powertrain-supplied tractive force. For constant speed $F_{tr} = F_d$.

Vehicle Deceleration with No Braking Required

Then $F_{tr} = F_d + Ma$, with the Ma term subtracting from the required powertrain-supplied tractive force.

Vehicle Deceleration with Braking

The powertrain provides no positive tractive force and braking must augment the drag force to adequately decelerate the vehicle. $F_{tr} = 0$, $F_b = Ma + F_d$.

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 $\int F \cdot ds$ (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, $\int F_{tr} \cdot ds = E_{tr}$, for a defined drive cycle including the portions of tractive energy needed to overcome drag losses, E_d , and braking losses, E_b . In summary these drive cycle energy quantities are calculated by

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

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].

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

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

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

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.

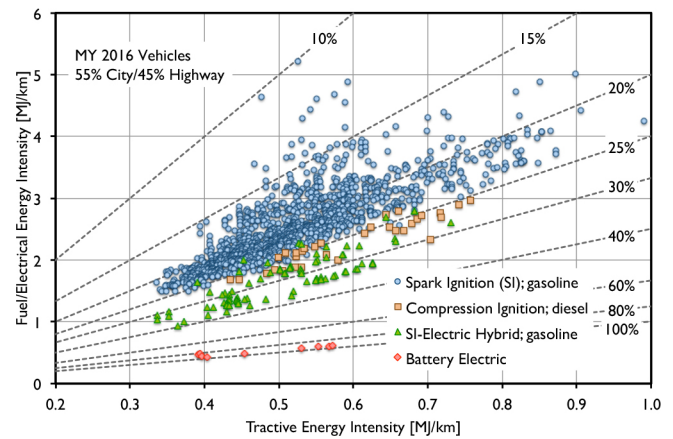


Figure 1. Fuel energy as a function of tractive energy; MY 2016 light duty vehicles.

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.

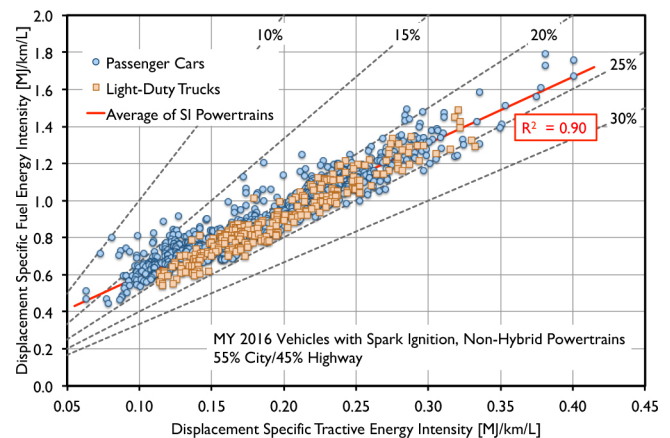


Figure 2. Displacement specific fuel energy vs. displacement specific tractive energy; MY 2016 light duty vehicles.

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 CO₂ 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.

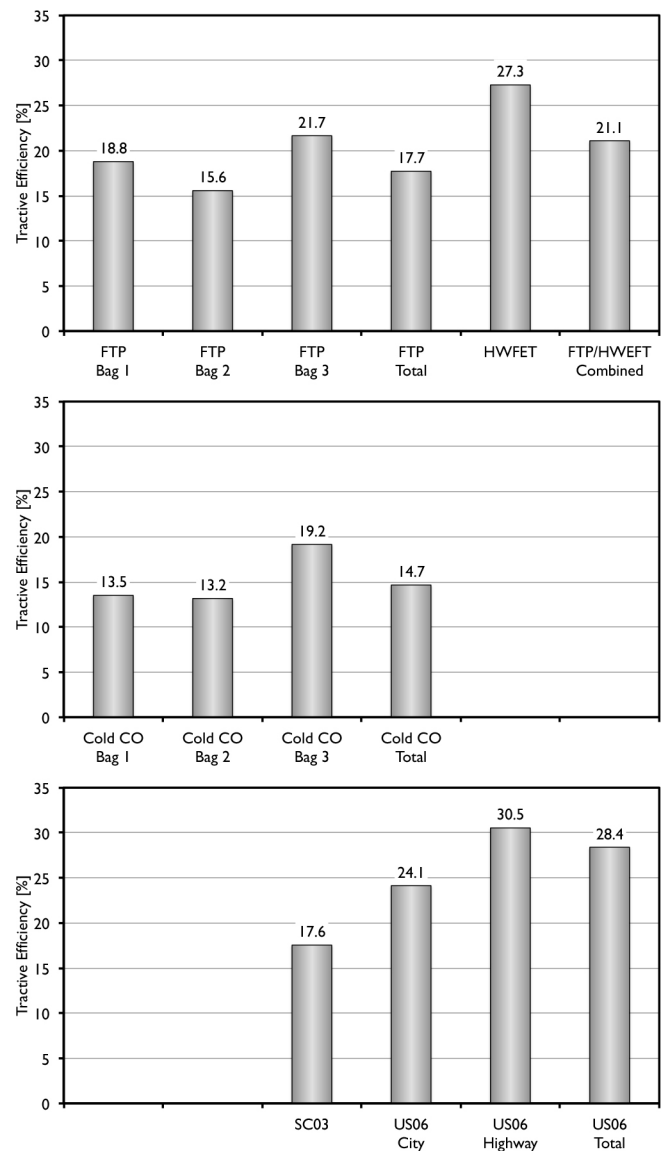


Figure 3. Tractive efficiency as a function of various drive cycles for a mid-sized cross-over utility vehicle.

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.

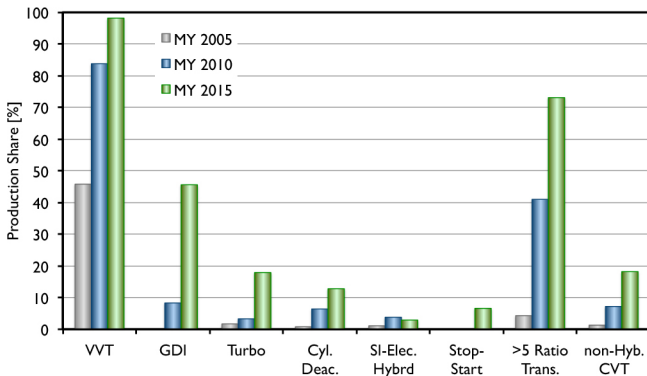


Figure 4. Powertrain technology market penetration for selected MYs [14]

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.

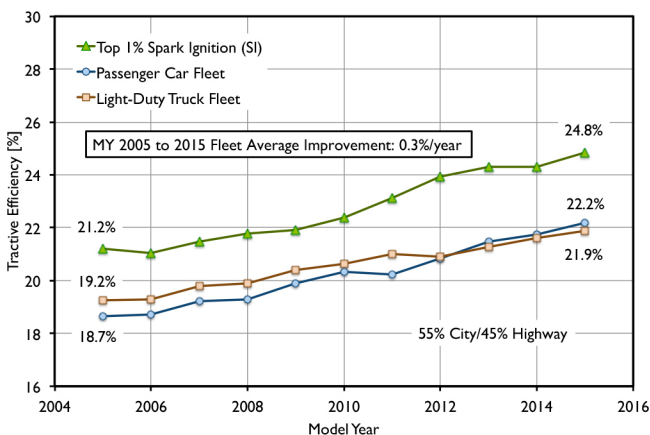


Figure 5. Tractive efficiency vs. model year

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].

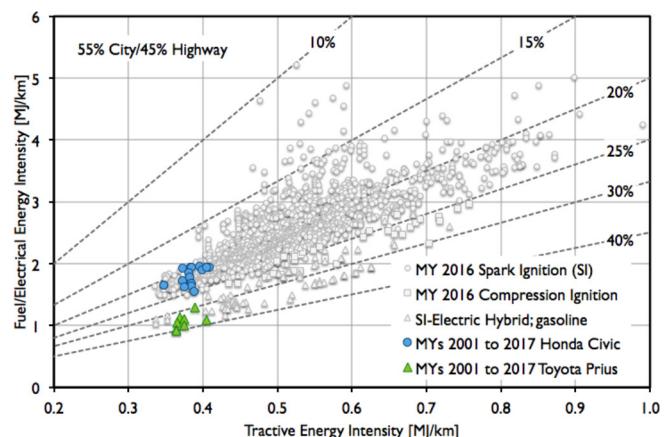


Figure 6. Model year 2016 light-duty vehicles are shown in the fuel energy tractive energy intensity domain. Successive Honda Civic and Toyota Prius models from MY 2001-MY 2017 are also included.

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.