

Vehicle Efficiency and Tractive Work: Rate of Change for the Past Decade and Accelerated Progress Required for U.S. Fuel Economy and CO₂ Regulations

John Thomas
Oak Ridge National Laboratory

ABSTRACT

A major driving force for change in light-duty vehicle design and technology is 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 (MY17) through 2025 (MY25) passenger cars and light trucks. The chief goal of this current study is to compare the already rapid pace of fuel economy improvement and technological change over the previous decade to the required rate of change to meet regulations over the next decade. EPA and NHTSA comparisons of the model year 2005 (MY05) US light-duty vehicle fleet to the model year 2015 (MY15) fleet shows improved fuel economy (FE) of approximately 26% using the same FE estimating method mandated for CAFE regulations. Future predictions by EPA and NHTSA concerning ensemble fleet fuel economy are examined as an indicator of required vehicle rate-of-change. A set of 40 same-model vehicle pairs for MY05 and MY15 is compared to examine changes in energy use and related technological change over the 10 year period. Powertrain improvements measured as increased vehicle efficiency, and vehicle “mass-glider” improvements measured as decreased tractive work requirements are quantified. The focus is first on conventional gasoline powertrain vehicles which currently dominate the market, with diesels and hybrids also examined due to their potential importance for CAFE compliance. Results indicate 10 years of progress for the studied vehicle set yielded reduced tractive effort of 5.6% and improved powertrain efficiency of 16.5%. Further analysis shows that this high rate of powertrain progress must increase by 90% or more in order to meet the 2025 CAFE standards. Comparison of MY15 vehicle FE values to CAFE target values is offered as well as conjecture on whether gasoline powertrains are adequate to meet regulations under reasonable assumptions.

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INTRODUCTION

The ensemble of Light-duty vehicles sold in the U.S. show a clear trend of improving fuel economy (FE) from model year 2005 (MY05) through MY15. Figure 1 shows FE data published by EPA and NHTSA [1]. The NHTSA values are slightly higher primarily due to NHTSA granting alternative fuel vehicle credits [1]. An estimated 26% gain in FE (21% drop in FC) is observed from 2005 to 2015. The basis of this unadjusted fuel economy data is EPA laboratory (chassis dynamometer) two test-cycle fuel consumption results (fuel consumed per unit distance) averaged for the ensemble of vehicles manufactured for the U.S. market each model year. The two cycles used are the city drive-cycle known as the Federal Test Procedure (FTP), and the highway drive-cycle known as the Highway Fuel Economy Test (HWFET). Furthermore, the test-cycle results are weighted 55% city and 45% highway (on a driving distance basis) to obtain the unadjusted fuel economy. This two cycle basis for unadjusted fuel economy is very important, because it is the basis of the 2017-2025 NHTSA CAFE and EPA GHG regulations (and the current standards). The weighted two-cycle scheme will also be referred to as the combined-cycle in this paper.

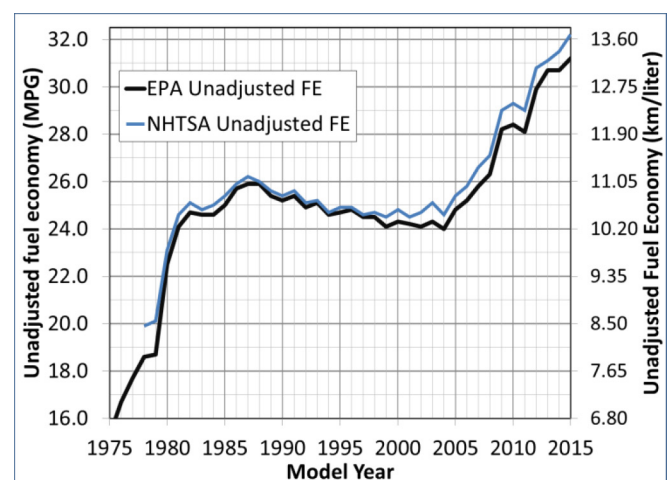


Figure 1. EPA and NHTSA unadjusted FE by model year is shown over 4 decades. A clear upward trend in FE beginning with MY05 vehicles is seen. Data is based on vehicle manufacturing data for each MY [1].

In a previous study [2], a set of MY05 and model year 2013 (MY13) vehicles were compared to examine progress and trends. The goal was to quantify and compare vehicle FE efficiency and required

tractive work for the FTP and HWFET cycles and to examine trends in related technological change. The current study builds from the previous study by expanding and updating (to MY15) the previous comparisons, and also relating results to CAFE/CO₂ standards as a driving force for increasing the rate of change in the vehicle fleet.

CORPORATE AVERAGE FUEL ECONOMY REGULATIONS AND CHALLENGES FOR FUTURE VEHICLES

Final rules were issued by the EPA and the Department of Transportation, NHTSA extending the CAFE program to reduce greenhouse gas (GHG) emissions and improve FE for MY17 through MY25 light-duty vehicles [3,4,5]. EPA's authority to set GHG emission standards comes from the Clean Air Act and the Energy Policy and Conservation Act and NHTSA establishes CAFE standards under the Energy Policy and Conservation Act, as amended by the Energy Independence and Security Act [3].

The calculation of the US EPA two-cycle or combined-cycle unadjusted fuel consumption (for a single vehicle) used as the basis for the NHTSA CAFE and EPA CO₂ regulations [3,4,5] is expressed by eqn. 1.

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

The combined-cycle fuel consumption $FC_{c\&h}$ can be expressed in units such as gallons/mile, kJ/km, energy per unit distance, or even translated to CO₂ grams per unit distance (the regulations are in g/mi for CO₂ and mpg for FE). The terms FC_{city} and FC_{hwy} are the unadjusted (sometimes referred to as "raw") values calculated from performing the FTP (city) and HWFET (highway) tests. The EPA estimates one U.S. gallon of gasoline produces 8887 grams of CO₂ [5,6,7] based on 100% gasoline fuel. The city and highway test procedures specify certification gasoline (no ethanol) to be used for fuel economy determination, so FE values are based on certification fuel, not the ~10% ethanol fuel (generally 3% lower heating value) consumers generally use.

The EPA and NHTSA regulations are based on vehicle footprint and are furthermore divided into separate categories for vehicles defined (for these regulations) as either cars or trucks. Figures 2 and 3 show graphically the year by year NHTSA FE target values [3,7] that vehicle FE will be measured against for credits or deficits. Note carefully that Figs. 2 and 3 represent the NHTSA targets, but also approximate the EPA CO₂ targets assuming 1) vehicles are gasoline fueled (diesel vehicles will be examined later, and must be treated differently) and 2) vehicles have been granted significant air conditioning GHG credits (Tables III-1 and III-2 in [3]). (EPA believes air conditioning technology will change over to low GHG factor refrigerants and low leak rates [3]). The dotted green lines labeled in Figs. 2 and 3 represent the EPA's base regulation target (assuming no GHG credits granted) for CO₂ emissions in 2025, transposed into FE for gasoline [3].

The regulations require that each vehicle manufacturer's product mix (sold), be measured against the corresponding FE/CO₂ target values. There are methods of averaging, carrying credits and deficits forward and backwards in time, trading credits between vehicle manufacturers and paying civil penalties to compensate for non-compliance. Special credit can be earned for electric powering (plug-in and all electric vehicles), flexible fuel vehicles, highly efficient air conditioning, and off-cycle technology (such as technology that improves cold weather FE, FE over the US06 cycle, or improves FE in ways not measured by dynamometer testing) [3,4,5].

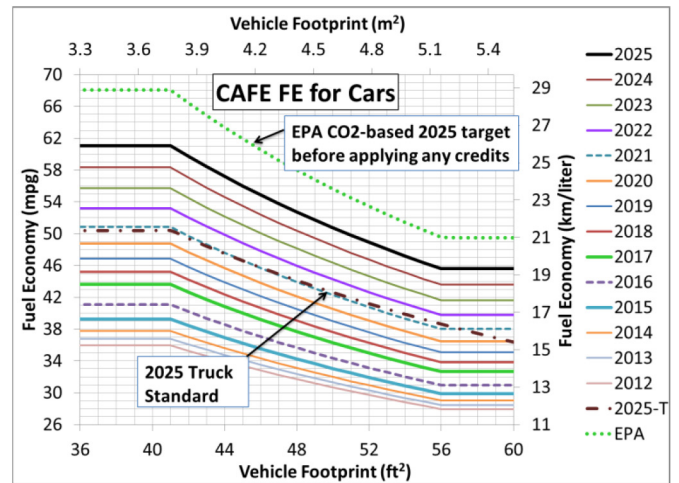


Figure 2. Footprint based yearly NHTSA CAFE target values for light-duty cars, 2012-2025. The 2025 Truck target values are included for comparison [3].

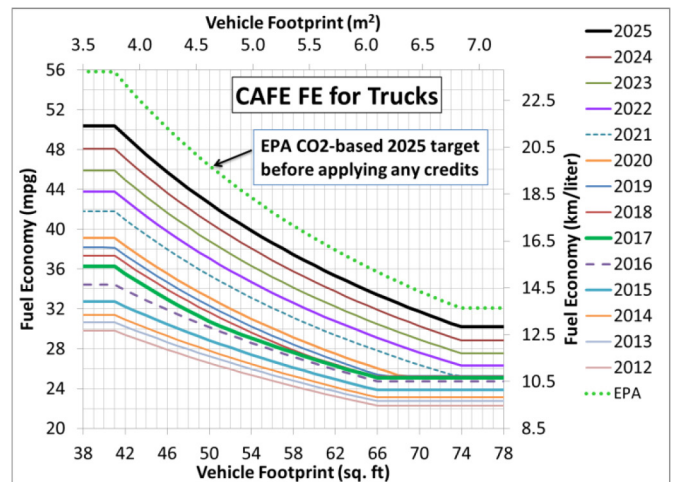


Figure 3. Footprint based yearly CAFE target values for light-duty trucks, 2012-2025 [3].

The CAFE requirements are complex and the actual results, even with full compliance, will depend on what manufacturers offer and what consumers purchase. In their regulatory announcements and in the final standards [3], NHTSA and EPA estimate FE values (for the ensemble U.S. fleet each MY) in future years for minimal compliance by automakers, assuming use of credits and other means of compliance (aside from civil penalties). The estimates [3] for attained FE are shown in Fig. 4 as the dashed and dotted curves. Different assumptions about projected vehicle fleet composition and

implemented credits result in the different estimates by NHTSA and EPA [3,4,5,8]. The solid red line is an EPA estimate for required FE if no credits were allowed (based on EPA CO₂ regulation, [3]). Also given in Fig. 4 are the EPA and NHTSA estimated historical (1995-2015) unadjusted FE for the yearly ensemble U.S. fleet (same data as Fig. 1) [1]. Linear projections based on the MY04-MY15 data are also shown, noting that no claim is made that a linear projection has any special validity to project past FE progress into the future. The projections are only to show need for future progress. (Alternatively, using percent gain from 2004 to 2015 as a multiplier would “bend” the extrapolated curves slightly upward changing the 2025 FE values to 40.0 and 41.6 mpg or 17.0 and 17.7 km/liter. This is an equally speculative method of extrapolation). Comparison of the Fig. 4 linear projections to the NHTSA and EPA projections for achieved FE implies that the rate of FE improvement must accelerate significantly compared to past progress to meet the regulatory requirements without civil penalties. In the 10 year period from 2005-2015 the (NHTSA and EPA) data show about a 26% increase in FE, which certainly could be considered as rapid progress. The increase for the 10 year period from 2015 to 2025 to meet regulations is estimated as **44% to 53%** using the various NHTSA and EPA values shown in Fig. 4. From this analysis, the rate of FE improvement in vehicles that has taken place over the last decade will need to increase by 70-105% over the next decade to meet CAFE/CO₂ regulations.

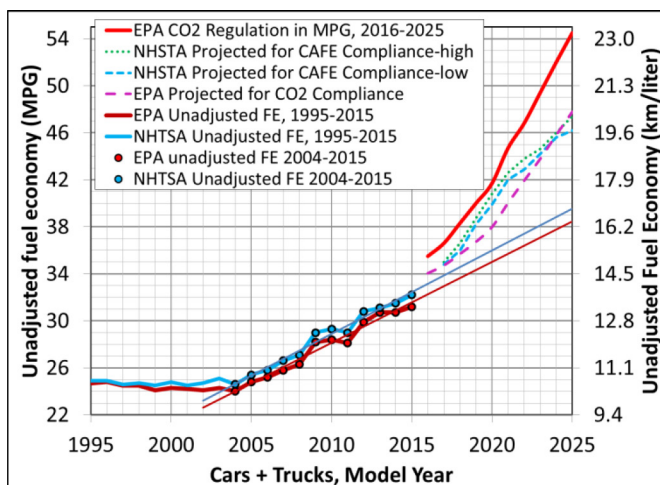


Figure 4. EPA and NHTSA historical unadjusted FE by model year is shown (Table 9.1 in [1]) along with the regulatory FE required without credits (Table III-1 in [3]) and estimates of FE assuming regulatory compliance with projected credits (Tables I-2, and III-3 in [3]). Linear trend projections based on FE data from 2004 to 2015 are also included.

VEHICLE FE, TRACTIVE WORK AND EFFICIENCY COMPARISON FOR 40 MY05 AND MY15 VEHICLES

The data represented in Fig. 1 is for the manufactured (and presumable sold) fleet of U.S. vehicles each MY. This is a vehicle mix that is in year-to-year flux due to changing consumer demand. Although this change is generally not large, it can change significantly over a decade. Table 1 compares the U.S. fleet makeup by selected groups of vehicles for MYs 2005 and 2014 based on

EPA data [1] with the chosen 40 vehicle set which will be studied. The cars (sedans, 2 seat vehicles) and car SUV categories comprise those vehicles designated as cars by EPA and NHTSA for CAFE/CO₂ regulations and the other three categories are deemed trucks for these regulations.

Table 1. Vehicle market proportions for EPA/NHTSA categories and the chosen 40 vehicle set.

Model Year	Cars	Car SUVs	Truck SUVs	Pickup Trucks	Mini-vans
2005 fleet	50.5%	5.1%	20.6%	14.5%	9.3%
2014 fleet	49.2%	10.1%	23.9%	12.4%	4.3%
40-vehicle sets (number)	47.5%, (19)	12.5%, (5)	22.5%, (9)	12.5%, (5)	5.0%, (2)

A comparison of vehicles given here will not focus on changes in vehicle preferences (although that is important), but will attempt to quantify metrics resulting from design and technology changes. To do this, a “static” set of vehicle models is chosen [2] which is fairly representative of the overall market, and changes to this vehicle set are quantified over a 10 year period.

Vehicles Examined

To examine vehicle evolution, 40 pairs of comparable vehicles were selected, with each pair composed of a MY05 and a MY15 vehicle.

All pairs retain the same manufacturer’s model name, have similar rated power or greater power for MY15 and are similar in weight. In five instances, two versions of the same vehicle were examined with differing powertrains or differing attributes. An example would be Toyota Camrys with 2.4 and 3.0 L engines and 5 speed transmissions for MY05 compared with 2.4 L and 3.5 L engines with 6 speed transmissions in 2015. Manual transmissions were excluded (they are less than 3% of the light-duty market [1]) as were diesel powertrains (about 1% market share [1]). One hybrid, the Toyota Prius, was included and the other 39 vehicles have conventional gasoline powertrains. The 40 vehicle sets cannot rigorously simulate the U.S. vehicle fleet characteristics for the chosen MYs (obviously because they differ), but the variety of vehicles does match many of the characteristics of MY14 fleet data reasonable well. Detailed information concerning characteristics of the chosen vehicle sets compared to the ensemble U.S. fleet for MY05 and MY14 is offered in Appendix A. A brief comparison of selected attributes is given in Table 1 and 2, to show the 40 vehicles selected as a group are similar to the ensemble fleet of U.S. vehicles.

Effort was made to choose the most popular vehicle models; therefore the most recent top selling vehicles that were also available in 2005 are included. (The most popular vehicles not included were the Ford Fusion and Chevrolet Cruze.). Note some vehicles are essentially represented by “sibling” vehicles (i.e. the Kia Optima is represented by the Hyundai Sonata).

Table 2. Selected (averaged) attributes for the ensemble US fleets [1] and the chosen 40 vehicle set.

Vehicle set	Unadjusted FE	ETW	Rated power	Engine displacement	4WD or AWD
	mpg, (km/l)	lb, (kg)	hp, (kw)	(liter)	market fraction
MY05 fleet, EPA	24.8, (10.5)	4059, (1841)	209, (156)	3.36	26.8%
MY05 40-vehicle study set	25.5, (10.8)	4100, (1860)	203, (151)	3.23	32.5%
MY14 fleet, EPA	30.7, (13.1)	4060, (1842)	231, (172)	2.95	32.6%
MY15 40-vehicle study set	31.4, (13.3)	4225, (1916)	237, (177)	3.03	32.5%

Explanation of certain nuances of using the EPA test car database should be mentioned. A minority of vehicles have multiple entries (in the EPA data), with slightly differing results but no indication of any vehicle differences. Some vehicles have entries for several configurations and/or differing equivalent test weights (ETWs, the dynamometer setting for vehicle weights EPA requires for each vehicle), but there is no other differentiating information. Generally when there is little indication of which choice to make among entries, (and the A, B and C coastdown target coefficients are identical) FE values were averaged or test FE values were selected that were closest to the average. Preference was given to the entries that helped match ETW for the MY05, MY15 pair. Some vehicles have no entries in a given year because a very similar model by the same manufacturer serves as a substitute (rarely an issue for the current vehicle choices), or there was no change in the vehicle from the previous year (apart from minor styling alterations). For the latter case, information was simply obtained from the previous MY database. In this study any data used from the MY04 or MY14 data base was believed to represent the corresponding MY05 or MY15 vehicle as well and the vehicle label FE values were verified to be identical, giving confidence to this assertion.

Vehicle Physics and Energy Considerations

This treatment of vehicle energy follows the methodology in a previous paper [2], and previous vehicle physics and energy analysis [9,10,11,12,13,14].

A vehicle driven on a chassis dynamometer experiences simulated road conditions. The vehicle supplies positive tractive driving force to the wheels, F_{tr} , which is opposed by the drag force F_d and inertia. The composite drag force, F_d , (rolling resistance forces, aerodynamic drag and other friction resistance) at velocity V , is described as

$$F_d = A + BV + CV^2 \quad (1)$$

Coefficients **A**, **B** and **C** are experimentally derived from coastdown testing techniques described in SAE Standard J2263 [15,16,17]. The term F_d is often referred to as the road load force. The resulting force balance equation for the vehicle can then be expressed as

$$\sum F = Ma = F_{tr} - F_b - F_d \quad (2)$$

The tractive force, F_{tr} , is considered only for positive values and is the force the tires apply to the dynamometer roller drums (or road). Negative force generated by the vehicle is deemed braking even if supplied in part by the powertrain (significant for hybrids). The braking force, F_b , becomes non-zero when deceleration exceeds that provided by the drag force. The term Ma is the vehicle mass (**M**) times the acceleration (**a**) and is the vehicle inertia.

The forces integrated over distance generate work or energy values for drive cycles using $\int F \cdot ds$ (work = force x distance), where **F** is a force and **ds** is an increment of distance. This allows calculation of the powertrain-provided tractive work over a given drive cycle and the opposing cycle work due to drag and braking losses. In summary three drive cycle energy quantities can be calculated by

$$\int F_{tr} \cdot ds = E_{tr} \quad (3),$$

$$\int F_d \cdot ds = E_d \quad (4), \text{ and}$$

$$\int F_b \cdot ds = E_b \quad (5),$$

and allows comparisons of vehicle tractive work requirements and drag energy dissipated over drive cycles [2].

The EPA test car database [18] provides the unadjusted FE values for vehicles tested over cycles allowing the amount of fuel energy, E_{fuel} , used during a test to be calculated. This database also contains each vehicle's test weight, ETW, which represents vehicle mass (including rotating mass), and the **A**, **B** and **C** road load force coefficients mentioned previously.

The efficiency for a specific vehicle operated over a test cycle is defined as

$$\eta_v = E_{tr} / E_{fuel} \quad (6)$$

with η_v being the ratio of powertrain-provided energy, E_{tr} , supplied to the drive wheels - to the fuel energy consumed, E_{fuel} . Sometimes this is referred to as tank-to-wheels efficiency.

Analysis Results for 40 Vehicle Set

Powertrain efficiency, η_v , and tractive work, E_{tr} , required was calculated (eqns. 6 and 3) over the FTP and HWFET cycles for all 80 vehicles. The EPA test car database has cycle FE results for most light-duty vehicles marketed in the U.S. over the FTP and HWFET. The certification gasoline used was assumed to contain 31.76 MJ/liter (lower heating value) in all cases to calculate fuel energy use (this value is found in previous SAE papers [2,13,14], is typical for ethanol-free certification gasoline purchased by ORNL and is close to U.S. DOE published values [19]). Results are plotted in Figures 3 and

6. The vehicle pairs in the figures are ordered from lowest to highest MY15 efficiency. The lone HEV (Toyota Prius) efficiencies which are off-scale in Fig. 5 are 32.5% and 34.3% for MY05 and MY15 respectively. Note that CUV is used for the SUVs or “crossover” utility vehicles when categorized as cars.

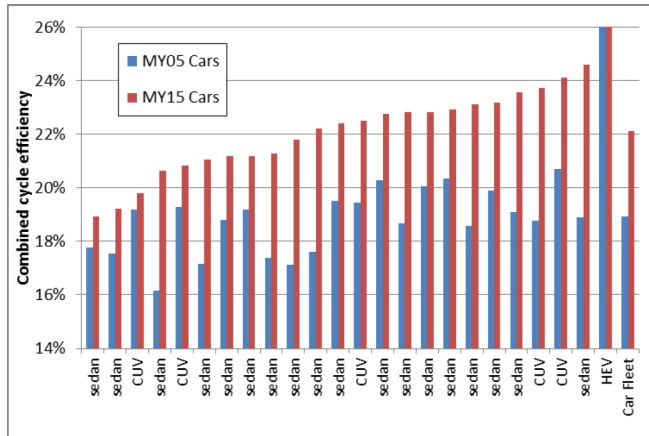


Figure 5. Vehicle combined city and highway powertrain efficiency by vehicle pair for cars. The MY 2005 and 2015 vehicles average 19.0% and 22.1% powertrain efficiency respectively.

It is observed from Figs. 5 and 6 that all vehicles examined improved in efficiency over the 10 year period. This improvement varies from 0.6% to 5.7% absolute efficiency improvement (the relative improvement varied from 3% to 30%). The lowest efficiencies for MY15 vehicles (~19%) are for popular V6 sedans, mainly because of the relatively low average load on the engines during the test cycles.

The result for tractive work per mile calculated for the combined city and highway cycle (again, proportioned as 55% city and 45% highway) are shown in Figs. 7 and 8. For 32 pairs, the required tractive work was less for the MY15 vehicle, and for 7 pairs tractive work increased for MY15 (one was virtually unchanged). Generally vehicles in this chosen set were somewhat larger in MY15 (by footprint) and averaged ~ 125 lbs. heavier, yet as a 40 vehicle set show a 5.6 % decrease in tractive work (based on the combined-cycle, Table 5). This indicates significant improvements were achieved in reducing overall vehicle drag (aerodynamic drag, friction, tire rolling resistance).

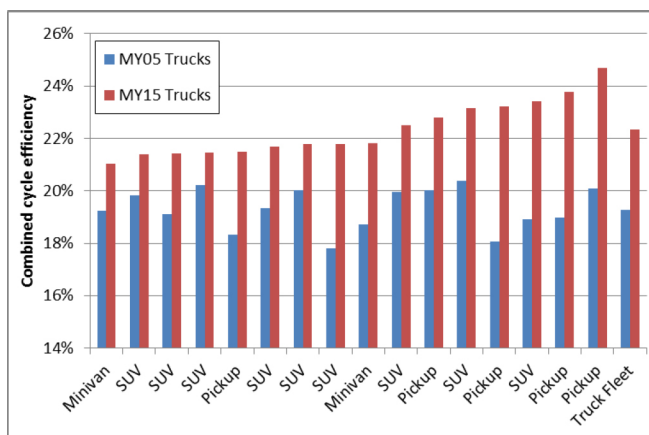


Figure 6. Combined city and highway powertrain efficiency by vehicle pair for Trucks. The MY05 and MY15 vehicles average 19.3% and 22.3% powertrain efficiency respectively.

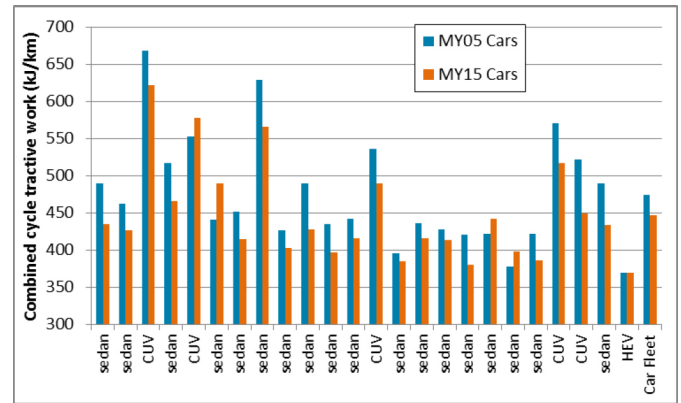


Figure 7. Combined city and highway powertrain tractive work per km by vehicle pair for cars.

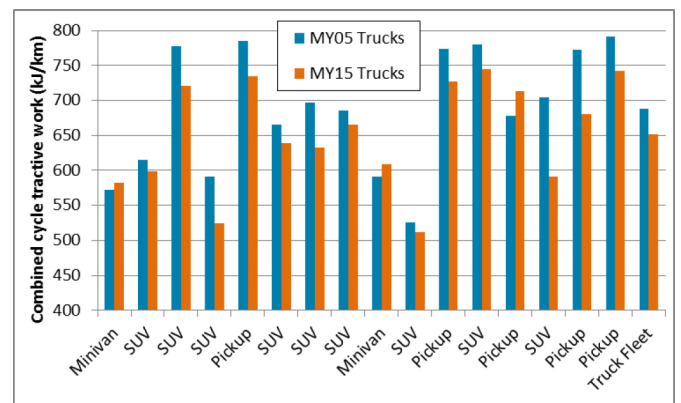


Figure 8. Combined city and highway powertrain tractive work per km by vehicle pair for trucks.

Table 3. Analysis results showing energy use change over the 10 year period for the selected set of 24 vehicles classified as EPA/NHTSA cars.

EPA/NHTSA Cars, 24 selected vehicles			
City Cycle	MY05	MY15	Change
Fuel use (kJ/km)	2968	2397	-19.24%
Tractive work (kJ/km)	474.8	458.8	-3.36%
Vehicle efficiency	15.99%	19.14%	19.67%
FE (mpg), {km/liter}	25.17, {10.70}	31.16, {13.25}	23.83%
Highway Cycle			
Fuel use (kJ/km)	1941	1555	-19.91%
Tractive work (kJ/km)	474.9	432.0	-9.03%
Vehicle efficiency	24.46%	27.79%	13.59%
FE (mpg), {km/liter}	38.48, {16.36}	48.05, {20.43}	24.86%
Combined-Cycle			
Fuel use (kJ/km)	2506	2018	-19.48%
Tractive work (kJ/km)	474.8	446.8	-5.91%
Vehicle efficiency	18.95%	22.14%	16.85%
FE (mpg), {km/liter}	29.81, {12.67}	37.02, {15.74}	24.19%