

Drive Cycle Powertrain Efficiencies and Trends Derived from EPA Vehicle Dynamometer Results

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ABSTRACT

Vehicle manufacturers among others are putting great emphasis on improving fuel economy (FE) of light-duty vehicles in the U.S. market, with significant FE gains being realized in recent years. The U.S. Environmental Protection Agency (EPA) data indicates that the aggregate FE of vehicles produced for the U.S. market has improved by over 20% from model year (MY) 2005 to 2013. This steep climb in FE includes changes in vehicle choice, improvements in engine and transmission technology, and reducing aerodynamic drag, rolling resistance, and parasitic losses. The powertrain related improvements focus on optimizing in-use efficiency of the transmission and engine as a system, and may make use of what is termed downsizing and/or downspeeding. This study quantifies recent improvements in powertrain efficiency, viewed separately from other vehicle alterations and attributes (noting that most vehicle changes are not completely independent). A methodology is outlined to estimate powertrain efficiency for the U.S city and highway cycle tests using data from the EPA vehicle database. Comparisons of common conventional gasoline powertrains for similar MY 2005 and 2013 vehicles are presented, along with results for late-model hybrid electric vehicles, the Nissan Leaf and the Chevy Volt.

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INTRODUCTION

Light-duty vehicles sold in the U.S. show a clear trend of improving fuel economy (FE), particularly from model year (MY) 2005 to the present. Excellent references elucidating these trends include "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 - 2013," published by the EPA [1], and "Average sales-weighted fuel economy of purchased new vehicles" (updated monthly), by the University of Michigan Transportation Research Institute [2]. Figure 1, taken directly from the EPA reference [1], shows a remarkable trend of FE improvement starting in MY 2004 or 2005. This specific trend influenced the current study, which compares gasoline powertrain efficiency changes from MY 2005 to MY 2013. An estimated 17.1% drop in fuel consumption (FC) which corresponds to a 20.6% increase in FE, was seen from MY 2005 to MY 2013 based on vehicle manufacturing data [1].

A major intent of this study is to examine the powertrain separately from other changes in vehicles (weight, rolling resistance, aerodynamics) and trends in consumer vehicle purchasing choices. Hybrid electric vehicles (HEVs) are examined as well, along with the Nissan Leaf and Chevy Volt to explore the large improvements in powertrain efficiency made possible with hybrid and electric drives.

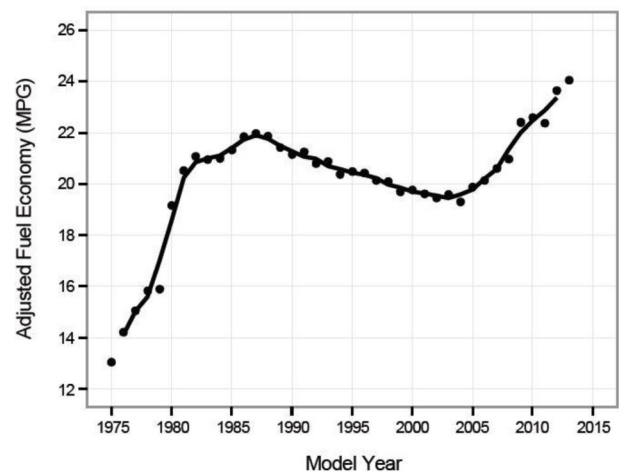


Figure 1. This figure, taken directly from reference 1 shows a clear upward trend in EPA adjusted FE beginning with MY 2004-5 vehicles. Data is based on vehicle manufacturing data for each MY.

A vehicle's published EPA fuel economy rating is determined by driving the vehicle over prescribed cycles on a chassis dynamometer. In the United States, city fuel economy is measured using the Federal Test Procedure (FTP). Highway fuel economy is measured using the Highway Fuel Economy Test (HFET). Three other relevant tests include 1) the US06 which is a high-speed, high-load test to confirm emissions compliance during aggressive driving, 2) the cold FTP which

measures emissions at 20°F ambient temperature and 3) the SC03 (conducted at 95°F) which examines the impact of air conditioning in hot weather. Typically, fuel economy results from these latter three tests are not reported, but EPA uses these to adjust the FTP and HFET results [3], and these adjusted fuel economy values are reported on the vehicle manufacturer's window sticker, in the Fuel Economy Guides and on the fueleconomy.gov website [4].

This work is part of a broad effort to provide accurate energy related information and consumer advice pertaining to light-duty vehicle FE and related issues on the fueleconomy.gov website [4]. In particular, web pages explaining how energy is used and dissipated when using light-duty conventional gasoline vehicles and HEVs are offered [4]. The current study provides updated information applicable to these particular webpages and furthers general understanding of vehicle energy issues.

APPROACH USING SIMPLE VEHICLE PHYSICS

Studies of vehicle energy use and dissipation using a basic physics approach have been offered previously [5, 6, 7, 8, 9, 10]. A very similar but much more detailed development of vehicle physics described below has been published recently by Sovran [5,6].

A vehicle driven on a chassis dynamometer experiences forces in the driving (horizontal) direction that determine (simulated) acceleration. The vehicle powertrain can supply a drive force at the wheels, F_{pt} , and the brakes can supply a force opposite the driving direction, F_b . The composite drag force, F_d , (rolling resistance forces, aerodynamic drag and other friction resistance) opposing motion of the vehicle at any velocity V , is modeled by the equation

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

and F_d is often referred to as the road load force. The coefficients **A**, **B** and **C** are experimentally determined by coastdown testing techniques described in SAE Standard J2263 [11, 12]. The resulting force balance equation for the vehicle can then be expressed as

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

where the driving direction is deemed to be the positive direction. In this treatment, the powertrain provided tractive force, F_{pt} , is considered only for positive values and is the force the tires apply to the dynamometer roller drums (or road in actual driving). When the tractive force is negative during a deceleration, this negative force is assumed to be supplied by

vehicle braking (even if actually supplied in part by the powertrain) and is always part of F_b in eqn. 2. The term Ma is the vehicle mass (**M**) times the acceleration (**a**).

It is useful to consider the possible applications of the above equation during a chassis dynamometer vehicle test. Four cases or situations are identified.

1. The vehicle velocity, V , is constant, therefore $F_{pt} = F_d$, $Ma = 0$, $F_b = 0$. Short periods at constant speed are present in both the city and highway drive cycles. This case includes the rather trivial case of idling, where the velocity and forces are zero, but fuel may be consumed by the powertrain.
2. The vehicle is accelerating, $F_{pt} = F_d + Ma$, with the Ma term adding to the required powertrain-supplied tractive force.
3. The vehicle is decelerating, but at a low rate such that braking is not required. Then $F_{pt} = F_d + Ma$, with the Ma term subtracting from the required powertrain tractive force.
4. The vehicle is decelerating and braking is required. In this case the powertrain provides no positive tractive force and the drag force is insufficient to adequately decelerate the vehicle over the particular speed trace segment. $F_{pt} = 0$, $F_b = Ma - F_d$. Any decelerating tractive force supplied by the powertrain is considered braking in this treatment [7]. The powertrain may or may not consume fuel under this condition.

The above development can be used to analyze forces, energy use and energy dissipation over standard test cycles. It is straightforward to integrate the forces over distance to obtain work or energy requirements throughout the cycles using $\int F \cdot ds$ (work = force $\times$ distance), where **F** is a force and **ds** is an increment of distance. This technique allows calculation of the powertrain-provided tractive work, $\int F_{pt} \cdot ds = E_{pt}$, for a defined drive cycle. This method can calculate the cycle work to overcome the drag losses and to overcome braking losses. In summary three drive cycle energy quantities can be calculated by

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

Furthermore, due to the chosen variable definitions in this simple development,

$$E_{pt} = E_d + E_b \quad (3)$$

for any drive cycle provided $V=0$ at the beginning and end of the cycle (see the essentially identical development leading to eqn. 28' in ref. 5 and eqn. 15 in ref. 6). Equation 3 simply states that the energy needed to propel the vehicle through the cycle, E_{pt} , equals the dissipated energy (in opposition) from the braking, E_b , and drag forces, E_d .

The EPA testcar database [13] provides the unadjusted fuel economy values for vehicles tested over cycles (sometimes referred to as the "raw" FE values [3,12]) 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 also known as the equivalent test weight (ETW) which is used to represent vehicle mass (including rotating mass), and the **A**, **B** and **C** road load force coefficients mentioned previously.

Powertrain efficiency for a specific vehicle operated over a test cycle can then be defined as

$$\eta_{\text{pt}} = E_{\text{pt}} / E_{\text{fuel}}, \quad (4)$$

with η_{pt} being the ratio of powertrain-provided energy supplied to the drive wheels - to the fuel energy consumed. There is at least one small flaw in this assertion. The fuel energy consumed in a drive cycle is used by the powertrain 1) to bring power to the wheels, 2) for the powertrain to "care for itself," (fluid pumping for cooling and lubrication, electrical load for spark, etc.) and also 3) to power the alternator for electrical loads not directly associated with the engine or transmission. Examples include dashboard lights, brake lights, etc. (it is assumed the headlights and climate control system are not operated, although daytime running lights may be utilized). There may also be minor losses associated with the air conditioner even when not in use (pulley friction) and similar losses. Such non-powertrain related energy consumption is likely quite small, and can perhaps be considered somewhat of a constant across vehicles. One could correctly assert that the above equation is a measure of the full vehicle's ability to use fuel to power the wheels, not only the powertrain. Nevertheless, the results should be very useful as a comparative powertrain metric.

POWERTRAIN EFFICIENCY ESTIMATES FOR MY 2005 AND 2013 CONVENTIONAL VEHICLES

Methodology

To examine recent powertrain evolution, 34 pairs of comparable vehicles were selected, each pair composed of a MY 2005 and a MY 2013 vehicle. All pairs retain the same manufacturer's model name and when feasible have similar rated power. In six instances, two versions of the same vehicle were examined with differing powertrains and other attributes. An example would be Toyota Camrys with 2.4 and 3.0 L engines and 5 speed transmissions for MY 2005 compared with 2.4 L and 3.5 L engines with 6 speed transmissions in 2013. In no case was there a significant drop in horsepower from MY 2005 to 2013 in a vehicle pair, and in most cases horsepower ratings increased (sometimes considerably). No manual transmission vehicles have been included here (manual transmissions comprised less than 5% of the light-duty market each year from 2009-2013, EPA ref 1, see p71) and no diesel powertrains were included (less than 1%

market share). There is no claim that merely examining 34 vehicles could somehow simulate the U.S. vehicle fleet characteristics for a given MY, but a variety of vehicles were included to achieve reasonable relevance (More information concerning characteristics of the vehicle sets considered and the ensemble U.S. fleet for MY 2005 and 2013 is offered in [Appendix A](#)). A breakdown by vehicle category is given in [Table 1](#).

Table 1. Distribution of conventional light-duty vehicle types.

Vehicle type	
compact cars	5
midsize & large cars	9
SUVs < 5000 lbs.	9
SUVs > 5000 lbs.	4
pickup trucks	5
minivans	2
Total	34

Some explanations regarding nuances of the EPA database are in order. 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 ETWs, but there is no other differentiating information. Generally when there is little indication of which choice to make among entries, preference was given to the entries listed first, or to the lowest vehicle configuration number. Many vehicles have no entries in a given year because a very similar model by the same manufacturer serves as a substitute (not 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 MY 2004 or MY 2012 data base was believed to represent the corresponding MY 2005 or MY 2013 vehicle as well. A check was made to verify that the given vehicle label FE values for MY 2012 and 2013 were identical, giving some confidence to this assertion.

Results for Conventional Powertrains

Powertrain efficiency was calculated (eqn. 4) for these 68 vehicles over the FTP and HFET cycles. The EPA testcar database has cycle test FE results for most light-duty vehicles marketed in the U.S. over the FTP and HFET, but the data is sparse for other test cycles. For this reason, only the FTP and HFET are considered in this work. The certification gasoline used was assumed to contain 31.76 MJ/liter in all cases (actual values are unknown but should not vary significantly from the assumed value) to calculate fuel energy use. Results are plotted in [Figures 2 and 3](#), with the powertrain efficiency plotted against an assigned vehicle pair number (1 to 34). [Table 2](#) presents some composite information for the chosen vehicle sets, along with a results summary.

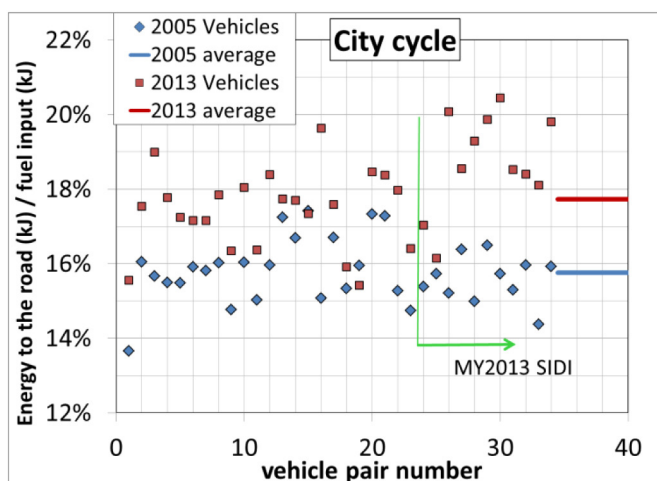


Figure 2. Vehicle powertrain efficiency estimates for the city cycle. The MY 2005 vehicles average 15.8% and the MY 2013 average 17.7%.

Table 2 values help characterize the aggregate vehicle set included in this study. There is a general rise in rated engine power of about 15%, a slight increase in average weight, a slight drop in engine displacement and an important change to a larger number of transmission speeds. Using averaged fuel use values revealed that the aggregate FTP fuel consumption dropped 13.2% from MY2005 to MY2013 (FE gain of 15.2%) and dropped 14.6% for the HFET cycle (FE gain of 17.0%). Part of the FC improvement is due to a reduction in tractive work (required powertrain energy, E_{pt}) needed for the test cycles. The MY 2013 vehicles showed a 2.3% and 5.9% drop in averaged tractive work for the FTP and HFET compared to the MY 2005 vehicles. The average weight of the MY 2013 vehicles is slightly larger than the MY 2005 value, therefore this drop in the required tractive work is due to the general trend of reduction in the (combined) contribution of aerodynamic drag and rolling resistance (see eqn. 3) from MY 2005 to MY 2013 (examination of vehicle pairs shows a drop in cycle tractive work in 28 of 34 cases).

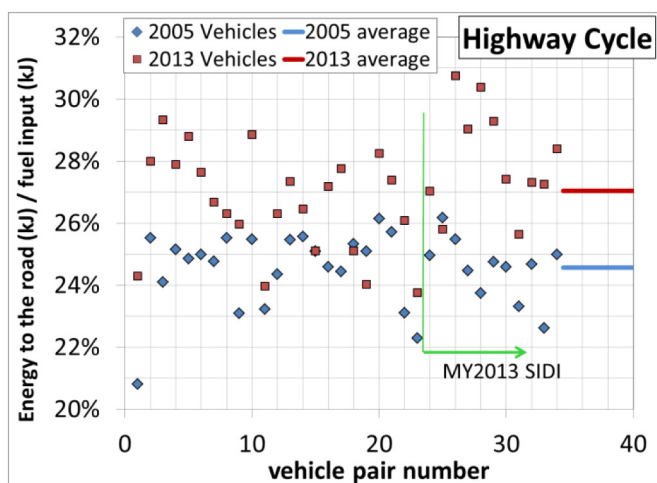


Figure 3. Vehicle powertrain efficiency estimates for the highway cycle. The MY 2005 and 2013 vehicles average 24.6% and 27.0% powertrain efficiency respectively.

Table 2. Aggregate vehicle attributes for 68 conventional vehicles used in this study.

Conventional Vehicle Attributes	MY 2005	MY 2013
Average ETW (lbs.)	4320	4415
Average rated power (hp)	216	248
Ave. engine displacement (L)	3.47	3.38
SIDI fueling	0	11
turbocharging	0	3
4 speed transmissions	19	2
5 speed transmissions	13	5
6 speed transmissions	1	22
8 speed transmissions	0	2
CVTs	1	3
Total transmissions	34	34
n/V, (engine speed)/(vehicle speed) at 50 mph	32.9	29.2
Average FTP Powertrain eff.	15.76%	17.73%
FTP Powertrain eff. range	13.7-17.4%	15.4-20.4%
Ave. FTP fuel use (kJ)	44086	38281
Ave. FTP tractive work(kJ)	6949	6787
Average HFET Powertrain eff.	24.57%	27.04%
HFET Powertrain eff. range	20.8-26.2%	23.8-30.8%
Ave. HFET fuel use (kJ)	39503	33753
Ave. HFET tractive work(kJ)	9704	9128

Significant gains are observed in how effectively powertrains use fuel energy to power the vehicles from MY 2005 to MY 2013. The results indicate about a 12.5% aggregate fuel-use improvement over the FTP cycle and 10% for the HFET (estimated from $\eta_{pt, 2013}/\eta_{pt, 2005}$). Note also that engine sizes in the vehicle pairs differed frequently, although the average engine displacement remained nearly the same. Six instances of significant engine downsizing were seen (12% to 30% reduction of displacement) and in 5 of 6 cases the powertrain efficiency improvement was among the highest observed of the 34 vehicle pairs. Also notable is a general drop in n/V, the engine speed (rpm) divided by the vehicle speed at 50 mph (average values are shown in Table 2). These n/V values are taken from the EPA database and show an average drop of about 11% from MY 2005 to 2013. All but six of the vehicle pairs showed some degree of downspeeding. This general downspeeding trend presumably contributes to improved powertrain efficiency (and FE). However, no significant correlation was found between paired vehicle n/V change and change in FTP or HFET powertrain efficiency.

Vehicles Using SIDI Technology and Others with High Powertrain Efficiency

There were 11 instances of MY 2013 vehicles employing direct injection technology (SIDI) engines. These are the 11 rightmost (red) points indicated in Figures 2 and 3. Many of the highest efficiency values are seen among the SIDI powertrains. The 11