

Predicting Light-Duty Vehicle Fuel Economy as a Function of Highway Speed

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ABSTRACT

The fueleconomy.gov website provides information such as “window label” fuel economy for city, highway, and combined driving for all U.S.-legal light-duty vehicles from 1984 to present. The site is jointly maintained by the U.S. Department of Energy and the U.S. Environmental Protection Agency (EPA), and also offers a considerable amount of consumer information and advice pertaining to vehicle fuel economy and energy-related issues. Included with advice pertaining to driving styles and habits is information concerning the trend that as highway cruising speed is increased, fuel economy will degrade. An effort was undertaken to quantify this “conventional wisdom” through analysis of dynamometer testing results for 74 vehicles at steady-state speeds from 50 to 80 mph. Using this experimental data, several simple models were developed to predict individual vehicle fuel economy and its rate of change over the 50-80 mph speed range interval. The models presented require a minimal number of vehicle attributes. The simplest model requires only the EPA window label highway mpg value (based on the EPA-specified estimation method for 2008 and beyond). The most complex of these simple models uses vehicle coastdown test coefficients (from testing prescribed by SAE Standard J2263) known as the vehicle Target Coefficients, and the “raw” (unadjusted) fuel economy result from the federal highway test. Statistical comparisons of these models and discussions of their expected usefulness and limitations are offered.

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INTRODUCTION

Consumer information and advice pertaining to light-duty vehicle fuel economy and other energy related issues is provided on the fueleconomy.gov website [1]. This site is jointly maintained by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy and the U.S. Environmental Protection Agency (EPA) to help fulfill their responsibility under the Energy Policy Act of 1992 to provide accurate fuel economy information to consumers. The site provides information on EPA fuel economy ratings for passenger cars and light trucks from 1984 to present and other relevant topics related to energy use such as alternative fuels, advanced vehicles, driving tips and vehicle maintenance tips. Recent crude oil price fluctuations and subsequent price fluctuations in gasoline and diesel fuels have renewed interest in vehicle fuel economy in the United States. User sessions on the fuel economy website have increased year-to-year, approaching 1 million in 2001, 5 million in 2004, and exceeding 30 million in 2008 and 2009. As a result of this renewed interest and the age of some of the references cited in the tips section of the website, DOE authorized the Oak Ridge National Laboratory (ORNL)

Fuels, Engines, and Emissions Research Center (FEERC) to initiate studies to validate, improve and expand these tips. This paper documents a portion of a study to better quantify light duty vehicle fuel economy as a function of steady-state highway cruising speed.

There has long been interest in fuel economy degradation with increasing highway speed. A national legislative attempt to lower U.S. oil consumption by limiting high speed driving took the form of the 1974 Emergency Highway Energy Conservation Act, which effectively created a nationwide maximum speed limit of 55 mph. In 1987, federal legislation allowed up to 65 mph for certain highways. The Act was fully repealed in 1995. Many states currently have speed limits restricted to 70 mph, but Texas set a speed limit of 85 mph for a new portion of a toll road in late 2012.

Maximum steady-speed fuel economy is generally achieved when a vehicle is operated at the lowest practical or recommended speed while in the highest gear (likely to be 40-50 mph for common vehicles). As speed increases beyond this point, fuel economy begins to drop largely due to increased aerodynamic drag. With the goal of providing good consumer advice and accurate information concerning fuel economy during highway driving, it was reasonable to focus

on speeds of 50-80 mph. Speeds below 50 mph are often not indicative of highway steady-speed conditions, but rather city driving or combinations of city and highway driving. Speeds above 80 mph were not considered because driving is rarely legal at speeds beyond 80 mph, and the important data obtained or generated for this study included speeds up to 80 mph but no higher. If desired, results from 50 to 80 mph testing and modeling could be extrapolated somewhat beyond 80 mph but with a caution that will be explained later.

Current website advice relevant to highway driving is to “observe the speed limit,” with the statement “gas mileage usually decreases rapidly at speeds above 50 mph,” and information on the estimated cost of driving faster. Choosing a lower highway cruising speed can only be meaningful when driving conditions allow the consumer to safely choose from a range of speeds. The driver requires conditions of low impedance to steady speed driving such as those realized on highways with lower traffic volumes, few intersections, etc. The intention of any website advice is to advocate safe driving, which excludes saving fuel by driving at a speed which significantly impedes the flow of traffic.

This paper presents simple data-derived models for predicting light-duty vehicle fuel economy based on a limited number of vehicle attributes. The motivation is to improve the factual information available to the consumer concerning fuel economy at highway speeds to allow consumers to make informed decisions.

SPECTRUM OF U.S. LIGHT-DUTY VEHICLES

A challenging part of this effort stems from the diversity of light-duty vehicles operating in the U.S. Some of the important variations are highlighted here.

Engine design variation. The U.S. fleet includes vehicle engines with 3 to 12 cylinders, with most having 4, 6, or 8 cylinders. Engine displacements (swept volume) vary from roughly 1 liter to over 6 liters. Modern vehicle fueling can be gasoline port injection, gasoline direct injection, or diesel direct injection. Furthermore, engines may be naturally aspirated, supercharged or turbocharged, have variable valve timing, and some engines feature cylinder deactivation. Engines also vary in compression ratio and recommended grade of gasoline (octane rating).

Additional vehicle attributes. Vehicles vary in weight, aerodynamics, transmission type (continuously variable transmissions [CVTs], manual transmissions, automatic transmissions, number of transmission gears, various gear ratios), wheel size, tire size and design, may be two-wheel or all-wheel drive, or have electric hybrid drives. The vehicle model types include sedans (cars), station wagons, sport utility vehicles (including “crossover” vehicles), minivans, trucks, 2-seat cars and others.

It follows from this diversity that light-duty vehicles may not simply fit into a few groups with very similar behavior in terms of fuel economy versus steady cruise speed.

AVAILABLE VEHICLE DATA

Data Sources

There has been an effort to obtain steady-speed vehicle fuel consumption data to improve understanding, and translate this information into advice and guidance available on the website. Under a non-disclosure agreement, Chrysler Group, LLC provided ORNL a data set for 51 vehicles tested at their Chelsea proving grounds. In addition, vehicle dynamometer testing was successfully conducted with an additional 23 vehicles at ORNL facilities. Combining the two data sets provided a basis of 74 vehicles.

The Chrysler-supplied data for 44 (of 51) vehicles consist of fuel economy values for speeds from 30 to 80 mph in 10 mph increments. For six vehicles, the data is in the same form but excluded the 80 mph value, and one vehicle lacked test data at 30 mph. Coastdown test derived Target Coefficients (prescribed by SAE Standard J2263 [2]) utilized during testing were supplied for 39 of the vehicles. In most cases the coefficients were produced by Chrysler conducting coastdown tests on the vehicle. Where Target Coefficients were not listed in the data, the matching vehicle in the appropriate EPA data base [3] was located and the listed values were assumed to apply. A further discussion on dynamometer coefficients is offered later.

Vehicle testing was performed at ORNL's Fuels, Engines, and Emission Research Center (FEERC). The vehicle research laboratory features a Burke E. Porter 300 hp motor-in-the-middle, two-wheel drive, 48 inch, single roll AC motoring chassis dynamometer. The laboratory is equipped with three dedicated emissions benches, each with conventional gas analyzers from California Analytical Instruments. Two benches can routinely measure raw undiluted emissions, and the third bench samples dilute exhaust from a constant volume sampling system (CVS, or dilution tunnel). The CVS bag sampler is equipped with conventional analyzers for CO, CO₂, NO_x, and THC, and can accommodate advanced emissions instrumentation for PM, oxygenates and other measurements. Steady speed fuel economy and emission levels can be calculated from the integrated emissions sampled from the CVS dilution tunnel, using carbon balance methodology that is similar to the bag sampling methodology specified by EPA and Code of Federal Regulations guidelines.

The vehicle tests at ORNL consisted of a warm-up phase, followed by operating the vehicles at steady speeds from 40 mph to 80 mph in 5 mph increments, with each speed held for at least 5 minutes. All vehicles were tested using the listed EPA Target Coefficients as the basis for the dynamometer settings.

The retail fuels used in the vehicles tested at ORNL varied in composition, including ethanol content (generally 10% or less ethanol), although many were tested with Federal Certification Gasoline. All retail fuels were analyzed by Southwest Research Institute, and the fuel economy results

were adjusted to put all data on the basis of a typical (ethanol free) Federal Certification Gasoline. Generally, ethanol content is the most significant factor that affects volumetric energy density and vehicle fuel consumption. Certification gasoline was used to generate the Chrysler supplied data.

Vehicle Attributes for Ensemble Data Set

The distribution of vehicles by EPA category for the 74 vehicle combined data set (51 from Chrysler, 23 from ORNL) is given in [Table A.1](#) in Appendix 1. Also listed is the population of vehicles classified by vehicle type, and engine and transmission design. The tested vehicles include model years from 2003 to 2012, and engine displacement ranged from 1.5 to 6.2 liters. While it would be ideal for the data set to represent the current light-duty vehicle mix in the U.S. fleet (if that were readily known) the data set does represent all important sectors of the current light-duty fleet.

Basic Data Form

For the current purpose, the only data considered were four fuel economy points (mpg) for each vehicle at speeds of 50, 60, 70 and 80 mph. The reasoning for this limited speed range is explained in the Introduction. The ORNL data includes speeds in 5 mph increments, but for simplicity and consistency when merging with the donated Chrysler data, other speeds (55, 65 and 75 mph) were ignored. Examples of data for six vehicles are shown in [Figure 1](#), and the behavior is observed to be approximately linear when plotted as mpg versus mph over the speed range. This linear approximation appears to hold true for most vehicles in the data set, however plots in terms of fuel consumption versus speed appear to be non-linear. This observation influenced the approach for some of the modeling effort.

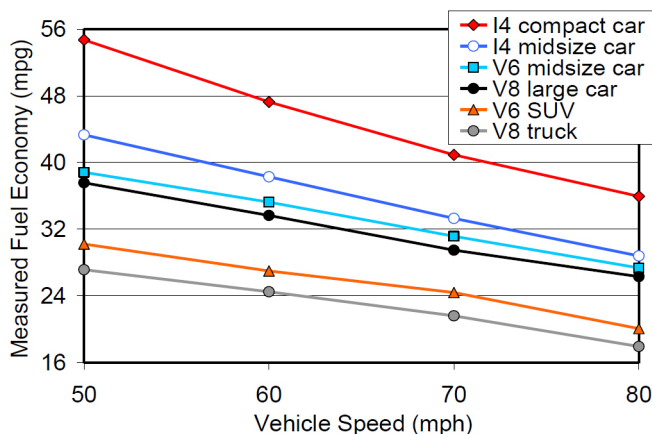


Figure 1. Example of data sets used to formulate models

Associated with each vehicle's fuel economy results is information covering the vehicle class, powertrain descriptors (including engine displacement and number of cylinders, transmission type and number of speeds, front, rear or all wheel drive; see [Table A.1](#)), test weight, and dynamometer coefficients. This information can be found in the EPA

vehicle testing data. Also obtained from the EPA database were results for the highway fuel economy tests for each vehicle in this study (used in the modeling effort).

Atypical Vehicle Behavior

Certain vehicles in the subject data set have design features likely to cause atypical fuel economy behavior compared to the conventional vehicle fleet. A list including discussions of these features follows. The final category (5) is for 2 "outlier" vehicles observed to display very obvious atypical behavior, but with no associated design feature specifically identified as the cause.

1. Cylinder deactivation. Three V8-powered vehicles feature cylinder deactivation, in which the engine can operate on only 4 cylinders at certain lower loads and utilizes all 8 cylinders at higher loads. For these vehicles there was a significant decrease in fuel economy between 60 and 70 mph for one vehicle and 70 and 80 mph for the remaining two vehicles, presumably due to the switch from 4 to 8 cylinder operation.

2. Protective enrichment. Under certain high load conditions, engines will purposefully operate with a fuel rich mixture to protect the engine and aftertreatment system from high temperatures. An ORNL-tested vehicle displayed protective enrichment at 80 mph (but not at 75 mph or less). This behavior was unanticipated but was observed for a vehicle with a 4 speed transmission with rather low gearing (engine was operating at 3500 rpm and elevated CO and hydrocarbon emissions were measured). Similarly, a vehicle in the Chrysler database was found to display virtually identical behavior in terms of fuel economy versus speed. While emissions data were not available for this vehicle, this behavior was assumed to be due to protective enrichment. Both vehicles show an unusually large decrease in fuel economy for 80 mph compared to 70 mph.

3. Diesel engine. The ORNL test data included a diesel Volkswagen Jetta, with fuel economy translated into gasoline equivalent values. One gallon of diesel fuel was estimated to equal 1.12 gallons of gasoline (based on volumetric energy content). However, diesel engines are known to operate at significantly higher thermal efficiency than gasoline engines under most conditions (due mainly to less pumping loss, lean-burn combustion and higher compression ratio). This vehicle was expected to be an "outlier" due to having a significantly higher powertrain efficiency at highway speeds compared to the gasoline vehicles.

4. Hybrid powertrain. Two hybrid vehicles, a Toyota Prius and a Ford Fusion, were among the ORNL tested vehicles. Both vehicles operated in a steady fashion using only the gasoline engine to power the vehicle over the 50-80 mph points of interest. For this reason they are deemed likely to show behavior typical of the conventional vehicle fleet. However, the Prius is known to be uniquely engineered for

very low drag and high fuel economy apart from the hybrid powertrain [4], and it is likely to stand out as atypical.

5. Other outlier vehicles. Two additional vehicles were observed to display quite obvious atypical (fuel economy versus speed) behavior, but in very different ways. Both are midsize 4WD V6 sedans, but no clear reason was found for the atypical behavior. Problems with the vehicle tests or unknown test variables (odd tires, vehicle modification) are possible explanations. In contrast, a third 4WD V6 sedan displayed behavior more typical of the majority of the vehicles.

Dynamometer Coefficients

Correct vehicle testing on a chassis dynamometer depends on the proper application of load (resistance to velocity and acceleration) to the vehicle. As the vehicle is driven, the drive wheels move a rolling drum which provides a resisting force at the tire/drum interface (via a sophisticated motor-generator system controlling the drum). A standard methodology has been specified by SAE Standard J2263 [2] and J2264 [5] to determine the correct dynamometer settings for a given vehicle at any speed. An on-road “coastdown” technique is used to determine all the drag forces on the vehicle from speed traces produced from coasting the vehicle in neutral. The end result of applying J2263 is a quadratic equation describing the road load force, F , under non-accelerating conditions as a function of velocity, V , expressed by

$$\text{road load force} = F = A + BV + CV^2$$

The coastdown methodology includes corrections to 20°C (68°F), 98.21 kPa (29.00 in-Hg) and still air. The coefficients A , B and C are known as the vehicle Target Coefficients, which are a property of the specific vehicle, (and will be used as a basis for three proposed models in this paper). The actual force on the drive wheels at any given time (opposing the direction of vehicle motion) also depends on an acceleration term, but for this effort only steady speed conditions are considered.

Dynamometer-specific settings are determined by another coastdown procedure with the vehicle installed on the dynamometer prescribed by SAE J2264. The process is repeated a number of times using a methodology which converges to a set of dynamometer parameters that cause the vehicle-dynamometer coastdown to be essentially the same as the vehicle on-road coastdown. This procedure is used to “program” the chassis dynamometer to apply forces correctly. These dynamometer-specific coefficients are known as Set Coefficients. Both Target and Set Coefficients are listed in available data from EPA, but only the vehicle Target Coefficients are specifically a vehicle property, and the Set Coefficients are unique to any given dynamometer-vehicle combination.

As a practical matter, a given vehicle is often dynamometer tested using the listed Target Coefficients in the EPA data base (to determine the proper Set Coefficients) which were produced for the same model of vehicle, or a very

similar model. On-road coastdown tests require a test track, specialized instrumentation, and are time and resource consuming. While vehicle-to-vehicle differences are expected, these coefficients are assumed to apply to all vehicles of that specific model or a very limited model range.

SIMPLE FUEL ECONOMY MODELS

Proposing and applying simple models to complicated systems will have obvious shortcomings, but may well have utility and give insight. A number of approaches to formulating data-derived models and variants were explored, and several interesting or relatively successful models are presented and compared. These models vary in complexity although all reduce to simple calculations. Along with the desire to develop a model that represents the data well, the end-use target is worthwhile consumer advice and information.

Vehicle Data Used to Develop and Compare Models

The method of using the available data for formulating, testing and comparing the models is listed as follows.

- The models are formulated by first excluding 8 vehicles mentioned earlier as atypical (3 with cylinder deactivation, 2 displaying protective enrichment at high speed, 2 AWD sedans with exceptionally odd behavior, and the diesel vehicle). Thus model formulations use data for 66 vehicles.
- Figures generally display results for all 74 vehicles in some manner for which data is available. Some selected vehicles are highlighted, many of which are “outliers” in regard to their mpg vs. speed behavior.
- Statistics concerning how well the data is fit by the models includes 70 vehicles, with those excluded being the 3 with cylinder deactivation and the diesel vehicle. These types of vehicles can be identified easily and would be known as exceptions that will likely not be modeled well by the current methods.

The above methodology was judged appropriate in order to optimize modeling of the 66 relatively “typical” vehicles rather than having results unduly influenced by vehicles with atypical behavior. Excluding or including the 8 vehicles mentioned was found to make only modest differences in the outcomes presented.

Naïve Estimate

As a simplistic starting point, the hypothesis was considered that all light-duty vehicles will behave the same way in regard to the percent change in fuel economy for a given increase in steady cruising speed. As shown in [Figure 1](#), fuel economy for most vehicles decreases linearly with increasing speed. This initial model is referred to as the Naïve Estimate because no vehicle-specific information is used. This model provides an initial standard against which other models can be compared, and is used to explore whether a

simple “rule of thumb” can have broad application. More precisely it was assumed there is consistent behavior for percent change in fuel economy for 10 mph increases in speed and this change is approximated by averaging the (individual) calculated percent changes in fuel economy for all considered vehicles. Speed increase comparisons of 50 to 60 mph, 60 to 70 mph and 70 to 80 mph were initially chosen for examination. The “model” reduces to the 3 numerical values for percent change in mpg for the respective increase in speed shown in [Table 1](#). The upper portion of [Table 1](#) has data for all 74 vehicles and the lower portion excludes the 8 atypical vehicles (numbers are based on 66 values for the 50 to 60 mph, and 60 to 70 mph cases; because data for 6 vehicles did not include 80 mph, the 70 to 80 mph case is based on 60 vehicles).

Table 1. Averages of mpg percent change for 10 mph incremental speed increases.

Speed increase	Percent mpg decrease for a given 10 mph increase, all 74 vehicles.		
	Average	Std. dev.	Data range
50 to 60 mph	12.4	2.2	6.9-18.3
60 to 70 mph	14.0	2.6	8.8-19.5
70 to 80 mph	15.4	3.0	10.8-26.0
all three speed increments	13.9	2.9	6.9-26.0
Speed increase	Percent mpg decrease for a given 10 mph increase, 66 vehicles included.		
	Average	Std. dev.	Data range
50 to 60 mph	12.4	2.1	8.1-18.3
60 to 70 mph	13.7	2.3	8.8-18.8
70 to 80 mph	15.0	2.2	10.8-21.0
all three speed increments	13.6	2.7	8.1-21.0

The even more “naïve” assertion can be examined that all three of the 10 mph speed increases produce the same percent change in fuel economy. This estimate is represented by the lower rows in each half of [Table 1](#). Note the wide range in behavior indicated by the standard deviation and ranges.

[Figure 2a](#) (upper plot) displays results from all 74 vehicles in comparison to the Naïve Estimate in terms of fuel economy change for 10 mph speed increments. The wide variation for the vehicle results would seem to indicate opportunity for better modeling. This result is not unexpected based on the broad range of vehicles being observed. The assertion that all three 10 mph speed increments produce the same percent change in fuel economy is challenged by both the averaged data and the individual vehicle results. A trend is observed that the percent change in mpg increases as the speed values increase.

[Figure 2b](#) (lower plot) repeats the data for the 50 to 60 mph speed comparison and adds speed comparisons of 50 to 70 mph and 50 to 80 mph. The top plot (a) is a very “close up” view compared to the bottom plot. The purpose in

showing both plots will be more apparent as additional models are presented.

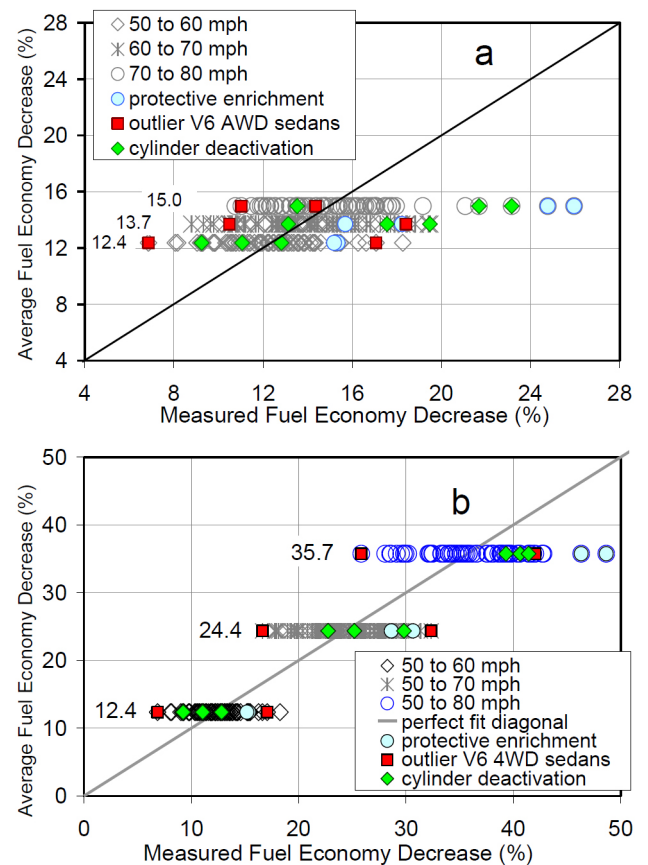


Figure 2. The Naïve Estimates are compared to the results calculated from the data set for selected speed increments.

Vehicles which were noted to display atypical behavior are highlighted in [Figure 2](#). The 2 vehicles which display protective enrichment and 2 of the 3 with cylinder deactivation stand out as having the largest percent change values, all 4 of which occur for the 70 to 80 mph fuel economy comparison. With these 4 values removed, the average percent change is 15.0%, so the trend of increasing values as speed increases remains. The other two vehicles highlighted (red) are the “outlier” AWD sedans, with one of these vehicles showing the lowest percent change in fuel economy for the speed increases examined.

A “rule of thumb” based on the data can be formulated. For example the statement that “most vehicles will lose 12-16% ($14\% \pm 2\%$) in fuel economy for a 10 mph increase within the speed range of 50-80 mph,” is true for 55% of the estimates based on the data. Using the interval 10-18% captures about 85% of the data estimates, and a broad 8-20% interval includes 98% of the data estimates. These rules of thumb can be useful, but only give the consumer a broad range of possible behavior rather than specific behavior for the vehicle they drive.

Model 1

A straightforward way to categorize vehicles is by the EPA/DOT label highway fuel economy value. For Model 1, the proposition is made that this value is indicative of the behavior for steady speed highway cruise. A model is offered using this highway mpg value as the lone vehicle attribute. From an information theory view, the label highway fuel economy value is directly influenced by the powertrain efficiency, vehicle weight, rolling resistance and aerodynamic drag. The attractive attribute of this simple approach is that only one easily obtained value is required to estimate the steady speed mpg vs. mph behavior of a vehicle.

An obvious concern (for Model 1) is that very different vehicles with the same EPA highway mpg value (e.g., an SUV and a large car) will be modeled as having identical behavior. As illustrated in Figure 3, two vehicles with the same EPA highway mpg can show diverging drive wheel power requirements with increasing speed, and fuel consumption would likely diverge in a similar fashion. The power requirements are calculated from the Target Coefficients for each vehicle.

Another observation is that label mpg values are discrete numbers. The label value is derived largely from the highway test “raw” mpg value, which is altered somewhat using a complicated method involving other vehicle tests having little relation to steady state cruising. The result is rounded to an integer [6]. Despite these concerns, it is useful to test the merit of such a simple modeling approach.

This model is realized by the following method. First the data set for each vehicle in terms of mpg versus speed is assumed to be linear (as shown previously in Figure 1), and a line fit is created using the least squares method. The relationship between mpg and speed, V (velocity), using observed data from each of the 74 test vehicles is put into the form:

$$\text{MPG} = a + b \times V \quad (1)$$

where “a” is the intercept, “b” is the slope of the linear regression model (MPG is the variable form of mpg). Among the 66 vehicles used to formulate this model, 60 have mpg measures for speeds at 50, 60, 70, and 80 mph. The remaining 6 vehicles have no mpg measured at 80 mph, therefore regression equations for those 6 vehicles were based on only 3 points, and all others were based on 4 points. The resulting linear equations all have a high goodness of fit, as measured by their R^2 statistics, indicating a linear relationship between V and mpg is a reasonable approximation.

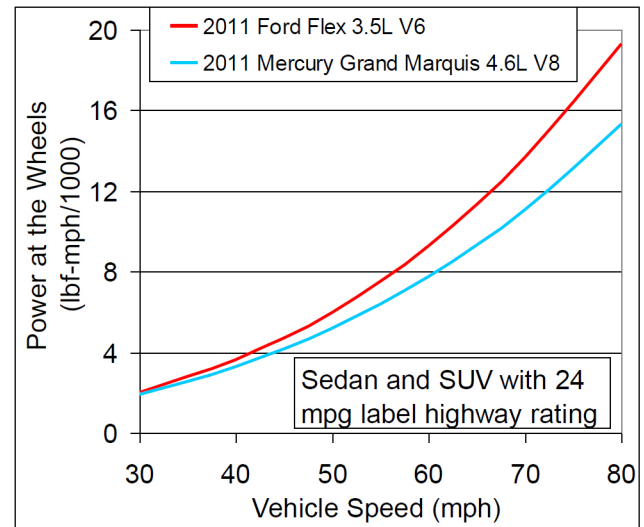


Figure 3. Calculated power at the wheels is shown for two different types of vehicle with the identical EPA label highway fuel economy and very similar “raw” highway fuel economy. (1000 lbf-mi/hr = 2.667 hp = 1.988 kW)

To generalize this formulation to any given vehicle (not only those captured under this study), requires a method to estimate the intercept and slope for the mpg versus cruising speed relationship (eqn. 1 for 50-80 mph). It is proposed that if a clear relation between the intercepts and slopes of vehicle-specific regression equations and the known EPA highway label mpg of those vehicles can be established, it would apply to any given light duty vehicle. This approach would produce a method by which a linear relation for mpg versus speed could be estimated for any light-duty vehicle.

This model uses a two-step approach. First establish individual functional relationships between (the regression equation) intercepts and slopes and the EPA highway mpg, and then combine the two functional forms to estimate mpg for the vehicle at a given speed. Mathematically speaking,

Intercept $a = f_a(\text{EPA highway mpg})$

Slope $b = f_b(\text{EPA highway mpg})$

Therefore, $\text{MPG} = f_a + f_b \times V$, where f_a and f_b are the functions as defined above, and V is vehicle speed.

The slopes and intercept values are plotted against the corresponding window label highway mpg value (obtained for each vehicle) as shown in Figures 4 and 5. The curve fit equations in Figures 4 and 5 are used to calculate the slope and intercept for the (linear) mpg versus speed behavior of a given vehicle based on the label highway fuel economy value. These curve fits appear to be reasonable, in that there is well-defined structure. The 8 vehicles excluded from the data used for curve fitting are shown as red points. (Using this same modeling method with fuel consumption as the basis did not work as well. Plots of fuel consumption versus speed were nonlinear, and a linear least squares method is not appropriate).