

Powertrain Efficiency in the US Fleet on Regulatory Drive Cycles and with Advanced Technologies

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ABSTRACT

The drive cycle average powertrain efficiency of current US vehicles is studied by applying a first principles model to the EPA Test Car List database. The largest group of vehicles has naturally aspirated engines and six speed planetary automatic transmissions, and defines the base technology level. For this group the best cycle average powertrain efficiency is independent of vehicle size and is achieved by the lowest power-to-weight vehicles.

For all segments of the EPA test, the fuel required per unit of vehicle work (the inverse of powertrain efficiency), is found to increase linearly with a basic powertrain matching parameter. The parameter is $(D/M)(n/V)$, where D is engine displacement, M vehicle mass, and (n/V) the top gear engine speed over the vehicle speed. The fuel consumption penalties in the City segments due to powertrain warm-up, aftertreatment warm-up, stop-and-go operation, and power-off operation are estimated.

The advanced technologies studied are turbocharging with downsizing, cylinder deactivation, and continuously variable transmissions. Cylinder deactivation is effective for vehicles with high power-to-weight ratio, whereas continuously variable transmissions are effective for small vehicles with low power-to-weight ratio. The benefits of turbocharging with downsizing are approximately constant across the range of vehicle performance, because the higher potential benefit at high performance levels is offset by a lower observed degree of downsizing.

The model can be used to estimate vehicle fuel consumption using a small number of design and drive cycle parameters, and can predict cycle average powertrain efficiency within one percentage point for the technologies studied.

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INTRODUCTION

As vehicle fuel consumption is a topic of continuing interest to vehicle users and to the authorities, there is an ongoing need to improve understanding of how vehicles use fuel. The discussion typically takes place at two very different levels. On the one hand the industry uses complex, detailed numerical models to provide the analysis of future vehicles incorporating many detailed improvements. On the other hand, one hears that "technology A is worth X% fuel economy", both inside the industry and in public discourse. Both approaches have limitations: the simple statements may be valid only under certain, unstated conditions, and the 'black box' nature of the numerical models does not necessarily improve understanding.

Simple models used together with rich data sets can help bridge this gap, by clarifying the primary factors involved, and by illustrating the status as well as any limitations of particular technologies.

For example, the large EPA Test Car List [1] database (TCL) can be used to study the properties of the predominant baseline technology, naturally aspirated spark-ignited (SI) gasoline engines with planetary automatic transmissions. As shown in [figure 1](#), the regulatory fuel

consumption is based on two different tests, City and Highway. The data in the TCL can be used to compute the vehicle work on the cycle, and the fuel economy or CO₂ emissions can be converted to energy use. It then becomes clear that (1) the work per unit distance is nearly the same on the two tests, (2) the fuel consumption is about 1.5 times higher on the City test than on the Highway test, (3) the powertrain efficiency on either test is not primarily a function of vehicle size, and (4) the efficiency on the Highway test can reach 30%, which is approaching the peak efficiency of the powertrain. More substantial analyses of this type are the subject of this paper.

Four stroke engines have two important properties that make simple models possible [2, 3, 4, 5, 6, 7]: (1) there is an approximately linear relation between fuel input and work output, and (2) this relation does not change much with engine speed.

It was shown that these properties are fundamental to how an engine operates [8], and they were used for a simple yet accurate analytic model of powertrain fuel consumption. This approach formed the basis for simple models of vehicle work and fuel consumption [9].

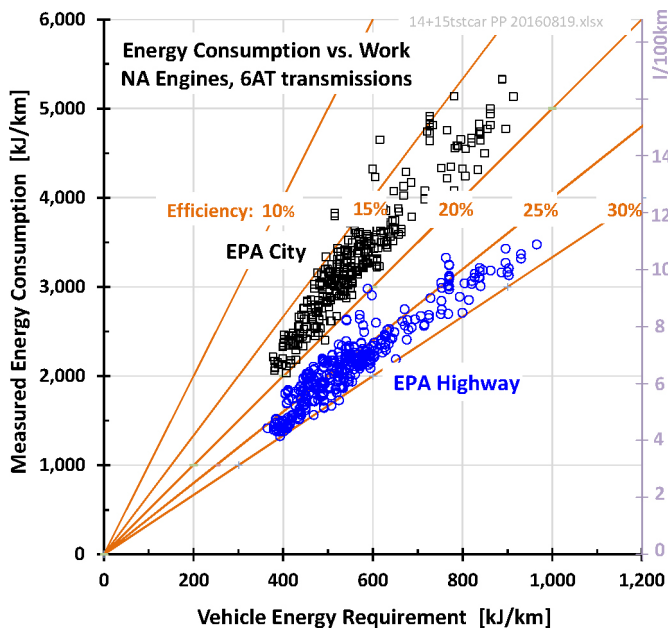


Figure 1. Fuel energy use on the EPA City and Highway tests as a function of the vehicle work done, for about five hundred 2014 and 2015 vehicles with naturally aspirated SI engines and 6-Speed automatic transmissions.

This paper uses the previously derived models and data sets to study the properties of the baseline technology in more detail, and to clarify the benefits and limitations of advanced technologies. The efficiencies of the base powertrains with naturally aspirated engines and 6-speed automatic transmissions are compared to those with (1) Continuously Variable Transmissions, (2) Cylinder Deactivation, and (3) Turbocharging with Downsizing. All comparisons use 2014 and 2015 data.

POWERTRAIN & VEHICLE MODELS

This model description includes key concepts and figures, but leaves out details and derivations which were previously published [8,9]. The system being considered consists of an engine feeding power through an automatic transmission to a vehicle during well-defined regulatory drive cycles. On these vehicles there is only minimal energy recuperation during braking, and the engine keeps running at idle.

Powertrain Fuel Consumption Model

A useful way to model fuel consumption is to express it in terms of energy use, and to normalize it in the same way the output of the engine is normalized, in 'mean effective pressure' units. The fuel energy flow rate, P_f , is defined as the fuel mass flow rate multiplied by the lower heating value of the fuel, H_f

$$P_f = H_f \dot{m}_f = \frac{1}{2} D n f_{umep} \quad (1)$$

where the fuel mean effective pressure f_{umep} is defined as the fuel energy used per engine cycle divided by the engine displacement. The factor $\frac{1}{2}$ results from four stroke operation. One can convert between the different ways of quantifying the conversion of fuel into work using

$$f_{umep} = H_f b_{mep} b_{sfc} = b_{mep} / \eta \quad (2)$$

where brake specific fuel consumption b_{sfc} is the fuel flow per cycle over the brake work per cycle, b_{mep} is the brake work per cycle over the displacement, and engine thermal efficiency η is brake work per cycle over fuel energy per cycle. Figure 2 shows f_{umep} vs b_{mep} for two typical automotive naturally aspirated (NA) SI engines. The data covers all loads and the range of engine speeds where most driving takes place (1250 to 2500 rpm). The measurements at the different engine speeds collapse onto a single straight line at part load. As the figure shows absolute fuel energy input versus absolute work output, lines of constant efficiency are straight lines from the origin.

The data are for a model year 2000 European four cylinder engine operating on 95 RON unleaded gasoline, and a 2013 US engine operating on 91 RON unleaded E10 fuel. Both engines were considered efficient at their respective introduction dates, and both have nearly identical efficiencies and compression ratios. Direct injection permits the more current 2013 engine to use the same compression ratio despite the use of low octane fuel. Increased friction from the high pressure injection has been offset by friction reduction in other design features.

The data in figure 2 can be summarized by a simple linear regression (dotted line), covering the low speed range and the load range from 0 to 7 bar. This means that nearly the whole engine speed and load range used in the EPA test cycles is very well described by a two parameter linear model.

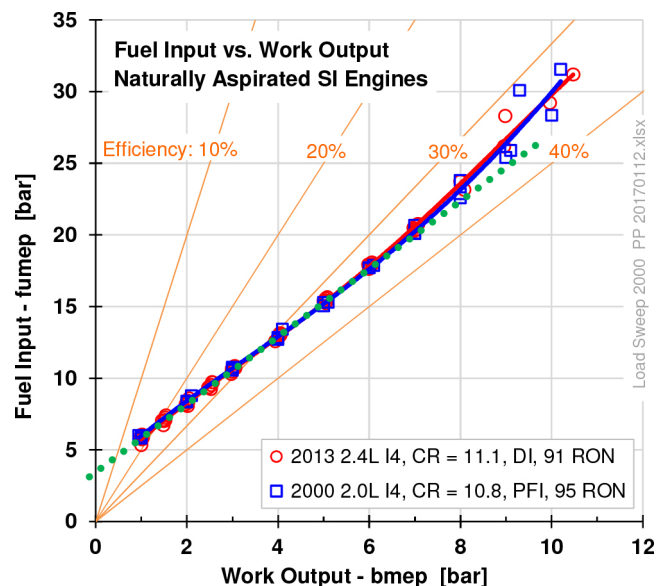


Figure 2. Normalized fuel input per cycle (f_{umep}) of two automotive naturally aspirated SI engines as a function of normalized load (b_{mep}) over the range of typical engine speeds, 1250 - 2500 rpm.

The linear relation observed between fuel input and work output was shown in [8] to be fundamental to the way an engine works, and may be written

$$bmep = \mu fume_p - lme_p$$

or

$$fume_p = (bmep + lme_p) / \mu$$

(3)

where the slope μ is the marginal efficiency of converting fuel to work. The loss mean effective pressure lme_p is the overhead for friction, pumping, and oil and water pump torque.

The two forms of Eq. (3) are mathematically equivalent, but reflect two different perspectives. The upper version shows the perspective of the process flow, of converting fuel to shaft power. It states that the fuel energy $fume_p$ is transformed into work on the piston with an efficiency μ , and then mechanical losses lme_p are subtracted to come to a net output work $bmep$. The lower version takes the engineering perspective and expresses how much fuel $fume_p$ it takes to generate an output $bmep$. It says that to the output $bmep$ one needs to add the mechanical losses lme_p , and then divide the sum by the efficiency μ to find the required fuel energy $fume_p$.

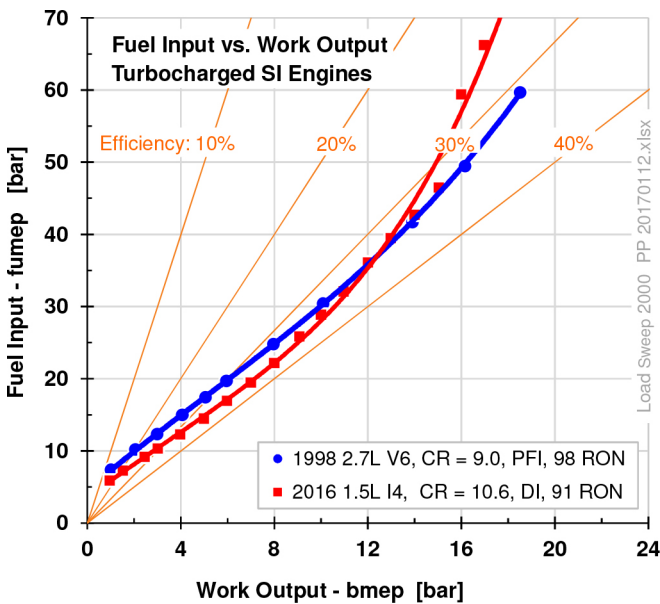


Figure 3. Normalized fuel input ($fume_p$) as a function of output ($bmep$) at 2,000 rpm for two automotive turbocharged SI engines.

Figure 3 shows $fume_p$ versus $bmep$ for two turbocharged (TC) engines. In the load range of 0 to 10 bar, the behavior of the two engines is linear, and similar to that of the NA engines in figure 2. The marked difference between the curves for the two engines reflects different design trade-offs between compression ratio, fuel octane, part-load efficiency and high load efficiency. The older turbocharged engine uses higher-octane fuel and achieves good efficiency under all conditions, including high loads where the fuel flow is highest. The 2016 TC engine utilizes a much higher compression ratio, which results in substantial savings at light loads. But the combination of higher compression ratio and lower octane fuel results in very high fuel flow at high loads. This approach will deliver favorable fuel consumption on lightly loaded government

tests. Under more realistic mixed use of high and low loads, the overall fuel consumption may not realize the savings predicted by the outdated government tests.

The marginal efficiency of turbocharged engines is substantially lower because they need lower compression ratios. Over a range of typical current engines, the marginal efficiency was found [6,7] to drop from an average of 0.42 for NA engines to 0.40 for TC engines, a 5% penalty.

The efficiency of transmissions with locked torque converters is also described very well by the offset (friction & pump) and slope (gear efficiency) linear model [8] when working in input and output power. As it does not introduce major new considerations and is quantitatively less important, the transmission efficiency will be ignored in the following simplified description for the sake of clarity.

Substituting the engine model (3) into the mep definition (1), the fuel energy rate is,

$$P_f = (P_t + \frac{1}{2} lme_p D n) / \mu$$

(4)

where P_t is the traction power needed to move the vehicle.

Vehicle Model

The vehicle road load force R may be split into the coast down deceleration rate $\delta_c(V)$ multiplied by the mass M ,

$$R = \delta_c(V) M$$

(5)

The advantage of working in terms of coast down deceleration rate is that it splits the force into a property that is very similar across vehicles, δ_c , and a simple size property, M . The deceleration rates of six very different vehicles, figure 4, are observed in benchmarking tests to be very similar.

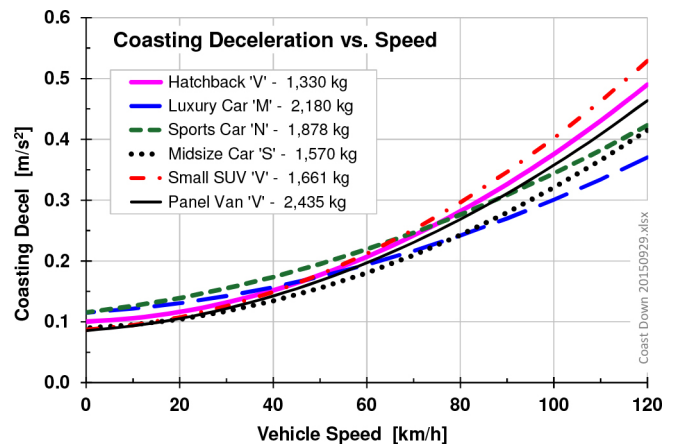


Figure 4. Coast down deceleration rates for a wide range of recent vehicles, from small car to large van.

When the road load is expressed in terms of the deceleration rate, the power needed to drive the vehicle can be written

$$P_t = \left[dV(t)/dt + \delta_c(V) + \nu g \right] M V \quad (6)$$

where ν is the grade and g is gravity. Government test cycles prescribe velocity as a function of time, $V(t)$, and therefore also acceleration dV/dt , so that in the absence of grades Vehicle Specific Power (VSP), P_t/M , is

$$P_t/M = \left[\frac{dV}{dt}(t) + \delta_c(V) \right] V(t) \quad (7)$$

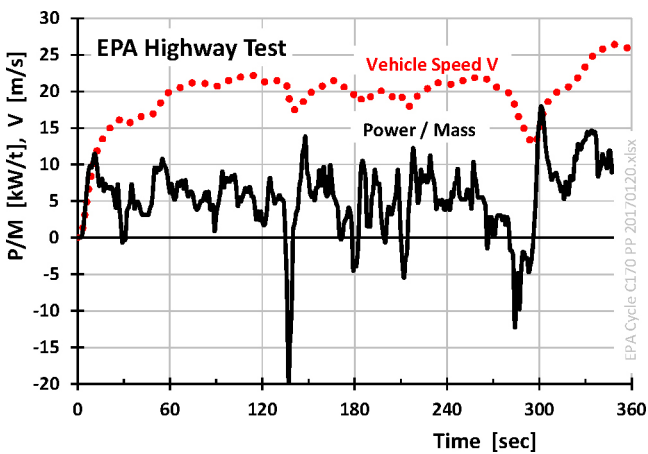


Figure 5. Speed profile $V(t)$ for the first 6 minutes of the EPA Highway test, and the corresponding Vehicle Specific Power profile $P(t)/M$, for road load properties typical of current vehicles.

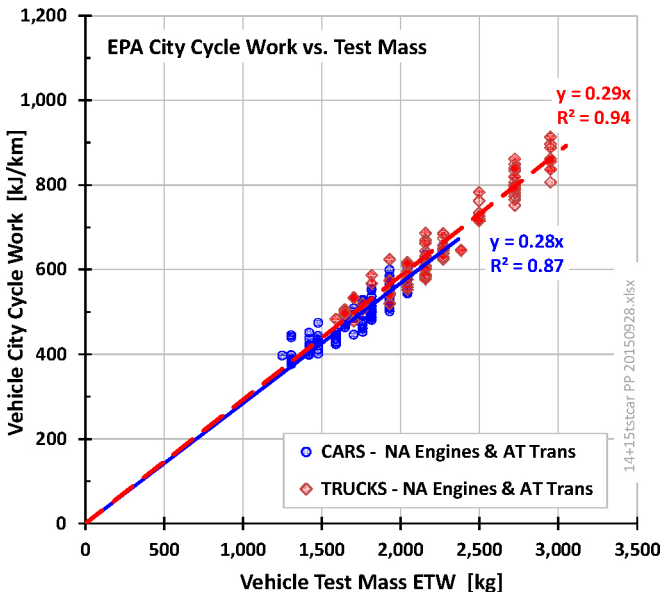


Figure 6. City test cycle work per unit distance as a function of vehicle test weight, for vehicles in the 2014 and 2015 EPA Test Car Lists.

The vehicle specific power is a function only of the velocity profile and the coast down deceleration rate. As most vehicles have very similar coast down deceleration rates, it follows that for a given test cycle most vehicles have similar vehicle specific power profiles.

The VSP profile on the EPA Highway test, figure 5, is by no means constant, but it is positive ('power-on') for large stretches of time, with isolated brief negative/braking ('power-off') episodes. In comparison, the City test consists of a rapid succession of accelerations, decelerations and idle periods, so that the VSP is alternately positive, negative and zero.

The work expended moving the vehicle through the prescribed cycle $V(t)$ is the time integral of the power, Eq. (6). Recognizing that conventional powertrains can only provide traction power to the vehicle but cannot recover it when needing to slow down, the integrals are only taken over those times when the traction power is positive. The cycle average work done per unit distance takes the form [9]

$$E/S = eM \quad (8)$$

where E is the work done, S the distance driven and e is the vehicle work per unit distance and mass, and has dimensions of acceleration.

The work per unit distance is a linear function of the coast down coefficients, and is unique for each drive cycle. It can be computed using the coast down coefficients in the TCL and the method of Sovran & Bohn [10], and is shown in figure 6 for the City test. It is largely a function of vehicle weight, as the coast down properties are typically similar at lower speeds as shown in figure 4. The Highway test has greater variability due to the variation in aerodynamic properties which is more pronounced at the higher speeds. The split in Eq. (5) and (8) of the road load and work into 'vehicle quality' factors δ_c and e , and the 'vehicle quantity' M is seen to be justified. The cycle average work per unit distance and mass e is about 0.3 m/s^2 for both the City and Highway tests.

Cycle Fuel Usage

On the EPA Highway test most of the driving is power-on, in gear, and with a locked torque converter. The previously developed powertrain model Eq. (4) for part load should therefore be applicable in this test.

The multivariable regression model corresponding to Eq. (4) is

$$F_H/S = [eM + aD(n/V) + b]/K \quad (9)$$

where a , b and K are estimated from the data, K is the total powertrain equivalent of the engine's marginal efficiency μ , and b is the remainder term, a catch-all for the effects that have not been modelled, such as the accessory loads.

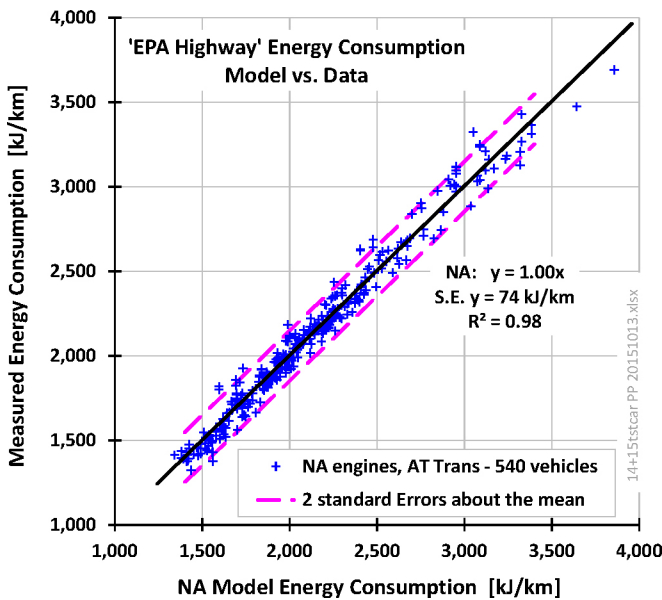


Figure 7. Comparison of the statistical model and the observed energy consumption on the EPA Highway test for vehicles with naturally aspirated SI engines and six speed automatic transmissions.

The model Eq. (9) was applied to the 500+ cars and trucks in the combined 2014 and 2015 Test Car Lists with naturally aspirated gasoline engines and six speed automatic transmissions which met certain data quality criteria [9]. The TCL contains the mass, engine displacement and gearing of all vehicles, as well as the road load coefficients, from which the cycle work can be computed. The model estimates are cross-plotted against the measured energy consumption in figure 7, and show a consistently good fit across the wide range of vehicles. The regression coefficients are very sharply defined and lead to an $r^2 = 0.98$. The standard error on the prediction amounts to about 4% for a typical car.

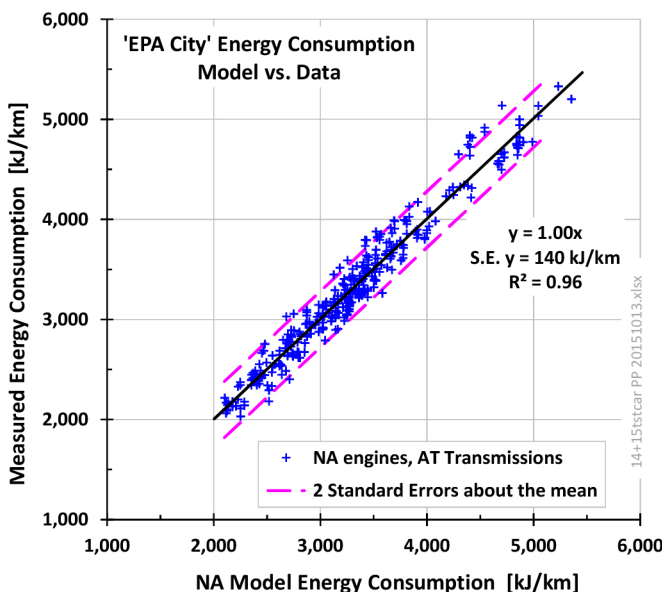


Figure 8. Comparison of the statistical model and the observed energy consumption on the EPA City test for vehicles with naturally aspirated SI engines and six speed automatic transmissions.

Because the Highway test is driven mostly power-on, in-gear with a locked torque converter, its properties are expected to be closely related to the powertrain properties. The observed in-vehicle conversion efficiency of $K = 0.39$ is very close to the expected value based on the powertrain data.

On the City cycle there are substantial periods of idle and low speed braking with engine on / torque converter open, so that the model Eq. (9) used for the Highway test needs to be modified. As the idle fuel consumption may be expected to be proportional to engine size, a term proportional to displacement is added,

$$F_c / S = [e M + a D (n / V) + b] / K + c D \quad (10)$$

The model estimates are cross-plotted against the measured City energy consumption in figure 8. The model works well across the range of vehicles, with $r^2=0.96$ and a standard error on the prediction of about 4% for a typical vehicle. The variability is somewhat higher than on the Highway test, because this cycle involves more driving situations and more different powertrain states, and they are handled somewhat differently from manufacturer to manufacturer. The overall marginal conversion efficiency for these vehicles on the City test is 0.29, or only about three quarters of the Highway test. In view of the power-on states driven with an open torque converter at each launch, this result is not surprising.

CYCLE EFFICIENCY OF THE REFERENCE VEHICLES

Beyond the ability to predict vehicle work and fuel consumption, understanding powertrain efficiency on a drive cycle is of particular interest to the powertrain community. The simplest way of looking at efficiency is to plot the fuel usage as a function of the work done, figure 1, for the vehicles with naturally aspirated engines and six speed automatic transmissions. The data show that the best vehicles reach about 30% efficiency on the Highway test, and most vehicles achieve between 25% and 30% efficiency. As the vehicle energy requirement scales mainly with vehicle mass, figure 1 shows that vehicle size and mass do not determine powertrain efficiency on this test.

On the City test the vehicle work per unit distance is very similar, but the fuel required is about 50% higher than on the Highway test. There is again no clear trend relative to vehicle size and mass. The best vehicles achieve 20% efficiency, and nearly all vehicles lie between 15% and 20%.

The base technology of naturally aspirated engines and six speed planetary automatic transmissions functions and provides the same efficiency across the whole range of light duty vehicles and beyond. While this conclusion may seem unremarkable, it will be shown that it does not necessarily apply to the advanced technologies considered later. The fact that the base technology works and provides the same efficiency across all vehicle sizes has become so accepted and ‘normal’ that this may have been erroneously assumed for newer technologies.

Inverse Powertrain Efficiency

A detailed study of [figure 1](#) shows that, in the vehicle work range with the most data points, there is a considerable range of efficiencies, 30 to 23% on the Highway test, and 20 to 15% on the City test, which is a drop of more than 20% relative to the best value in both tests. To understand the reason for this one needs to be able to compare vehicles. The traditional way to make vehicles comparable is to use efficiency, which is just the ratio of work to fuel. However, the models [Eq.\(9\)](#) and [\(10\)](#), which were found to work well, show that the fuel used is proportional to the sum of the work done and of a powertrain matching term on the Highway test, with an additional term proportional to displacement on the City test. To understand the breakdown of the fuel use and at the same time normalize for vehicle size, this suggests looking at the inverse of efficiency, the ratio of fuel over work (F/E),

$$F_H / E = [1 + (a/e)(D/M)(n/V) + b/eM] / K \quad (11)$$

With this metric, the efficiency can still be read off a second scale. But because the fuel is now in the numerator, and a linear model of fuel usage is available, the breakdown of the fuel usage can be shown on a linear scale. The model [Eq.\(11\)](#) predicts that normalized fuel per unit work increases linearly with the powertrain matching parameter (D/M)(n/V).

In the TCL, engine displacement is given in liter (l) and vehicle mass in pounds (lb), which are converted to metric tons (t). The gearing n/V in is given in (rpm/mph), which is converted to (rev/s)/(m/s), so that the final unit is 1/m. The matching parameter (D/M)(n/V) then has common metric units of (l/tm), equivalent to 10^{-6} (m²/kg).

City and Highway Efficiency

The Inverse Powertrain Efficiency (ratio of fuel used over work delivered) is plotted in [figure 9](#) as a function of (D/M)(n/V) for the five hundred vehicles with the baseline technology on the Highway test. The fuel used is therefore normalized by the first factor in [Eq.\(9\)](#), and plotted as a function of the second one. The data show the expected trend of increasing fuel use per unit work as the size and gearing of the powertrain increase. In relation to the work done, the fuel used increases from about 3.5 times for the smallest powertrains, (D/M)(n/V) = 1.5, to 5 times for the largest powertrains, (D/M)(n/V) = 3.5.

The sharply defined model makes it possible to break down the fuel use. The fuel needed for the vehicle cycle work (first term in [Eq.\(9\)](#)) is about 2.5 times the work. The observed marginal efficiency of $K \sim 39\%$ in the vehicle data is a good match to the powertrain data as exemplified by [figure 2](#). The rest of the fuel goes to cover the mechanical losses of the powertrain itself (second term in [Eq.\(9\)](#)), and increases in proportion to powertrain size and gearing. It is about equal to the work delivered for the smallest powertrains, but is 2.5 times the work delivered for the largest powertrains. The figure also shows that most of the Highway cycle vehicle work is road load, and only a small fraction is acceleration.

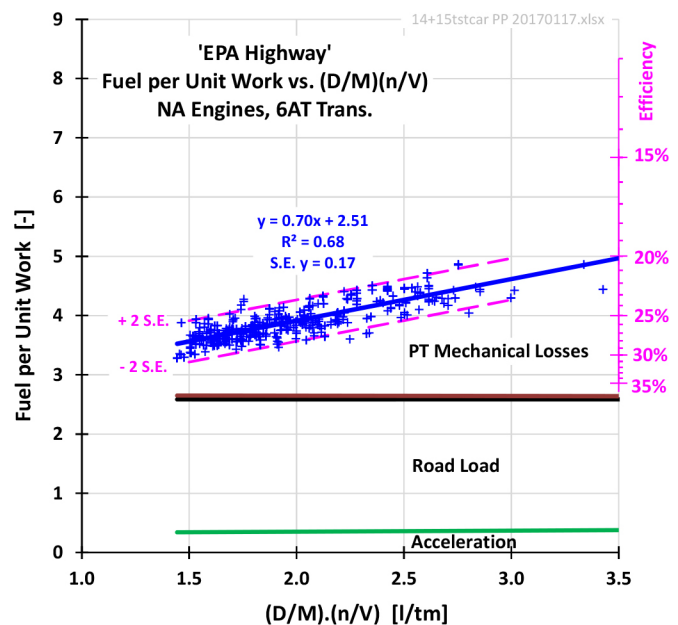


Figure 9. Breakdown of the observed energy consumption per unit work delivered on the EPA Highway test for vehicles with six speed automatic transmissions, as a function of the powertrain matching parameter (D/M)(n/V).

The corresponding plot of Inverse Powertrain Efficiency delivered on the City test, [figure 10](#), shows that the fuel required is about 50% higher. The fuel required to deliver the vehicle acceleration and road load work is also about 30% higher (~ 3.4 versus 2.6). The acceleration work is about equal to the road load work, and the estimated fuel to cover powertrain mechanical losses is about the same as on the Highway test. The major difference is in the fuel apportioned to the power-off conditions and the unexplained residual.

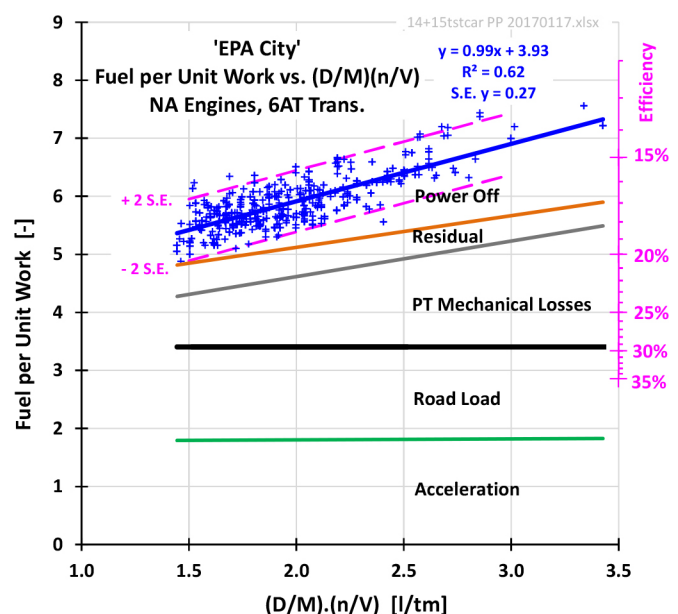


Figure 10. Breakdown of the observed energy consumption per unit work delivered on the EPA City test for vehicles with six speed automatic transmissions, as a function of the powertrain matching parameter (D/M)(n/V).